

Hidden dibaryons in one- and two-pion production in NN collisions

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Abstract

Processes of one- and two-pion production in NN collisions are considered in connection with excitation of intermediate dibaryon resonances. In particular, relative contributions of the conventional meson-exchange and dibaryon excitation mechanisms in the reaction $pp \rightarrow d\pi^+$ are investigated in detail. Inclusion of the intermediate isovector dibaryon resonances is shown to essentially improve the description of experimental data for this reaction, provided the soft meson-baryon form factors consistent with πN elastic scattering are used. Manifestation of the intermediate isoscalar and isovector dibaryons in the two-pion production processes is also studied. The role of the isovector dibaryon resonances in the reaction $pp \rightarrow pp\pi\pi$ is discussed for the first time. An explanation of the observed strong differences between two-pion production cross sections in pn and pp collisions based in part on the analysis of dibaryon structure is suggested.

Keywords: Nucleon-nucleon interaction, Pion production, Dibaryon resonances, ABC effect

1. Introduction: Dibaryons are “to be or not to be”?

Search for dibaryon resonances and their manifestations in hadronic and electromagnetic processes is a long-standing problem which takes its origin in the late 1970ies (see the basic Refs. [1, 2, 3, 4] and also reviews [5, 6, 7]).

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In that time, the first experimental indications appeared for existence of the number of dibaryon states. In particular, in elastic scattering of polarized protons $\vec{p} + \vec{p}$, the signals of a whole series of isovector dibaryons in 1D_2 , 3F_3 , 1G_4 , etc., partial waves were found [8, 9, 10] (see also later experimental works [11, 12, 13]). Besides that, rather convincing though indirect indications for an isoscalar dibaryon with quantum numbers $I(J^P) = 0(3^+)$ were found in measurements of the outgoing proton polarisation in the deuteron photodisintegration process $\gamma d \rightarrow pn$ at energies $E_\gamma \simeq 400\text{--}600$ MeV [14, 15, 16].

It is worth emphasizing that the first theoretical prediction of dibaryon states based on SU(6) symmetry was done still in 1964 in the pioneering work of Dyson and Xuong [17], appeared only several months after Gell-Mann's first publication on the quark model of hadrons [18]. In the following, a number of dibaryon states were also predicted and investigated within the QCD-inspired models [19, 20, 21, 22, 23]. At the same time, a series of theoretical works appeared (see, e.g., [24, 25, 26, 27]) where dibaryon degrees of freedom (d.o.f.) in different hadronic processes were considered. In those works, however, the dibaryon parameters were adjusted *ad hoc* to describe the observables of a particular process under consideration, with no explicit relation to both microscopic quark models and the description for other types of hadronic processes, where the same dibaryon resonances might participate.

From the other hand, it was demonstrated [28, 29, 30, 31, 32, 33] that the basic features of some hadronic processes, such as $\pi d \rightarrow \pi d$, $NN \leftrightarrow \pi d$, etc., where the claimed dibaryon resonances were expected to manifest themselves, can be described within the framework of conventional meson-exchange mechanisms without any dibaryon contributions. Hence, it turned out to be very difficult to draw some definite conclusions about existence (or absence) of dibaryon resonances and their role in hadronic processes. The situation was worsened by the fact that, in spite of extensive searches, in that time (in 1980–90ies) no quite convincing experimental evidences for dibaryons were found [34]. As a result, the general interest to the problem faded away.

Recently, however, the situation around dibaryons began to change rapidly. A number of new inspiring results have appeared, that have led to some kind of renaissance in the area of dibaryon physics. One of such results has been the prediction of a strange H -dibaryon in the lattice QCD calculations (see, e.g., [35, 36]) and the following initiation of a big experimental program at JPARC [37] aimed at searching for the H -dibaryon. It is worth mention-

ing that unsuccessful experimental search for this dibaryon in previous years (since its first prediction by Jaffe [1])) was one of the reasons for scepticism against the existence of dibaryons (see, e.g., [34, 38]).

The second not less important result is related to the non-strange dibaryons. It is the recent experimental finding of the isoscalar dibaryon resonance $\mathcal{D}_{03}(2380)$ with $I(J^P) = 0(3^+)$ (first predicted by Dyson and Xuong [17]) in the two-pion production reactions $pn \rightarrow d\pi\pi$, $dd \rightarrow {}^4\text{He}\pi\pi$ and $pd \rightarrow {}^3\text{He}\pi\pi$ [39, 40, 41, 42, 43] and an explicit relation of this resonance to the well-known Abashian–Booth–Crowe (ABC) effect [44, 45], i.e., an anomalous enhancement in the cross sections of these reactions just above the two-pion threshold. Although the interrelation between this dibaryon formation in the 2π -production reactions and the ABC effect was predicted already in an old paper [15], the reliable experimental data that confirmed this prediction have appeared only 30 years later. This has become possible mainly due to considerable progress achieved in experimental technique (simultaneous registration of three and more particles in coincidence, measurements in full 4π geometry, etc.).

The remarkable features of the $\mathcal{D}_{03}(2380)$ resonance are its mass, lying much (80 MeV) lower than the threshold of simultaneous excitation of two Δ isobars, and its rather narrow width $\Gamma_{\mathcal{D}_{03}} \simeq 70$ MeV. Just these features made it possible to separate almost unambiguously the resonance signal from the background given by the conventional meson-exchange processes (mainly the t -channel Δ – Δ excitation). It is generally not surprising that a resonance being short-range in nature is manifested most pronouncedly in the processes accompanied by large momentum transfers, where the contributions of peripheral meson-exchange processes are rather low. This seems the main reason for success in finding the \mathcal{D}_{03} resonance just in the two-pion production processes. However, the new polarization measurements along with the modern partial-wave analysis revealed this resonance also in np elastic scattering [46, 47]. Thus, the isoscalar dibaryon $\mathcal{D}_{03}(2380)$ is quite reliably established up to date.

Presently there are continuing searches also for other dibaryon states including those with higher isospins $I = 2$ and 3 [48], the supernarrow dibaryons lying below the pion-production threshold [49], etc. These searches will definitely be further stimulated by the recent discovery of pentaquarks by the LHCb Collaboration [50]. Pentaquarks as well as dibaryons had very painful history, so their experimental finding strongly supports existence of exotic multiquark states and gives a hope to find more such states in the

near future. However, besides searching for more exotic dibaryon states in particular processes, it is important to reveal the interrelations between different dibaryons and different processes where they can participate, as well as to investigate the role of dibaryon d.o.f. in short-range NN correlations and in the basic short-range nuclear force, in general.

It has been suggested recently [51] that dibaryons can transform into each other through meson emission and absorption. In particular, it was shown that the essential role in the decay of the isoscalar resonance $\mathcal{D}_{03}(2380)$ into $d\pi\pi$ channel may be played by an intermediate state $\mathcal{D}_{12}(2150) + \pi$, where $\mathcal{D}_{12}(2150)$ is an isovector dibaryon with $I(J^P) = 1(2^+)$ (also predicted in [17]). This mechanism of the $\mathcal{D}_{03}(2380)$ decay was further incorporated in the rigorous three-body Faddeev calculations for the $\pi N\Delta$ system [52]. If the dibaryon resonances really exist, such transitions between them seem to be quite natural. In fact, one may present a lot of examples of similar transitions in the traditional field of baryon resonances, such as the Roper resonance decay via an intermediate Δ isobar: $N^*(1440) \rightarrow \Delta + \pi \rightarrow N + \pi\pi$.

However, the isovector dibaryons, including $\mathcal{D}_{12}(2150)$, have not yet become commonly accepted objects. On the one hand, there are numerous indications for these dibaryons obtained from both experimental data and several independent partial-wave analyses (PWA) for the processes $pp \leftrightarrow pp$, $\pi^+d \leftrightarrow \pi^+d$ and $pp \leftrightarrow \pi^+d$ [53, 54, 55, 56, 57, 58, 59, 60]. Besides that, a robust dibaryon pole corresponding to $\mathcal{D}_{12}(2150)$ was found in the most recent theoretical calculation [61] within the framework of Faddeev equations for the πNN system. On the other hand, some previous amplitude analyses (see, e.g., the analysis [62, 63] of experimental data for the reaction $pp \rightarrow np\pi^+$) did not find a sufficient phase variation in the dominant $NN \rightarrow N\Delta$ partial waves which could be a signature of dibaryon resonances. The conclusions against broad dibaryons drawn from the above analysis were later criticized in a number of works (see, e.g., [64, 65, 55]), however, were supported again in [66]. In fact, the dibaryon $\mathcal{D}_{12}(2150)$, if it exists, lies very near to the $N\Delta$ threshold and has a width $\Gamma_{\mathcal{D}_{12}} \simeq 100\text{--}120$ MeV close to that of the Δ isobar. So, one needs very accurate experimental data to distinguish between a true resonance pole and a threshold cusp in this case. Unfortunately, as was stated in [66], the existed data for $NN \rightarrow N\Delta$ amplitudes contained typical uncertainties of 5–10%. Moreover, there is a severe theoretical uncertainty in determining the $NN \rightarrow N\Delta$ phase shift because of the large width of the Δ isobar. Perhaps due to these uncertainties, different analyses of experimental data on reactions $NN \rightarrow NN\pi$ have led to controversial conclu-

sions about existence of a true dibaryon pole near the $N\Delta$ threshold. Other isovector dibaryons, though lying higher than $N\Delta$ threshold, have smaller excitation strengths and larger widths. As a result, the isovector dibaryon resonances are highly uneasy to identify even in the well studied reactions $pp \rightarrow d\pi^+$ and $pp \rightarrow np\pi^+$ where the large momentum transfers suppress the conventional peripheral processes. The new high-precision experiments on one-pion production are obviously needed to shed light on the problem of isovector dibaryons, as was the case for two-pion production experiments which revealed the isoscalar resonance $\mathcal{D}_{03}(2380)$ [39, 40, 41, 42, 43]. Nevertheless, some new important information about both isovector and isoscalar dibaryon resonances could however still be obtained from the analysis of different hadronic processes where the same dibaryons can be excited. Such an analysis is a subject of the present study.

In the present paper we tried to clarify the question of intermediate dibaryon contributions in hadronic processes, paying the most attention to one- and two-pion production in NN collisions. The present work is focused on three main topics: (i) revealing the interconnections between different dibaryon resonances and investigating their possible mutual transformations; (ii) studying the relative role of the same dibaryons in different hadronic processes; (iii) clarifying the interrelation between the resonance (dibaryon) and background (meson-exchange) contributions.

The basic motivation of the present study was a general idea that the processes with large momentum transfers, e.g., $NN \rightarrow d\pi$, $NN \rightarrow d\pi\pi$, etc., proceed with a significant probability through generation of the intermediate resonances, such as dibaryons, owing to their longer lifetime compared to that of direct (non-resonance) processes. As the net effect of interaction is defined by an integral over the interaction time, it should be easier to transfer a large momentum in a resonance-like process than in a direct process without time delay.

From the other hand, the NN collisions accompanied by a high momentum transfer must be very sensitive to the short-range components of the NN force. Thus, a consistent description of such processes should apparently take into account the internal nucleon structure, because one deals here with the inter-nucleon distances $r_{NN} \lesssim 1$ fm, where the quark cores of two interacting nucleons are closely overlapped with each other. However, an explicit account of quark and gluon d.o.f. in description of hadronic processes like $pp \rightarrow d\pi^+$, $pn \rightarrow d\pi^+\pi^-$, etc., would lead to the huge complication of the whole picture.

At the same time, it was found [67, 68] that the basic effects of the nucleon quark structure in the NN interaction can be adequately described in terms of dibaryon rather than quark d.o.f. In such an approach, the NN -interaction t -matrix includes several resonance terms of the form $|\phi_a\rangle\langle\phi_a|/(E - M_D^{(a)} + i\Gamma_D^{(a)}/2)$, where $M_D^{(a)}$ and $\Gamma_D^{(a)}$ are the mass and width of a dibaryon of the a -th kind, i.e., with a particular set of quantum numbers, and $|\phi_a\rangle$ is the dibaryon form factor, which represents the vertex function for the a -th resonance decay into NN , $NN\pi$, or $NN\pi\pi$ channels. Such a description does not require an explicit account of the quark-gluon d.o.f. and is directly related to the variables of the respective hadronic channel. So, although the nature of dibaryon resonances is still a subject of debates [38], their introduction for effective account of quark d.o.f. at short NN distances appears to be quite reasonable.

In Sec. 2 the one-pion production process $pp \rightarrow d\pi^+$ is analyzed from the conventional viewpoint. The basic difficulties in description of this process within the framework of the conventional meson-exchange approach are demonstrated. Such a detailed investigation is necessary for clarifying the interplay between the background (meson-exchange) and resonance (dibaryon) contributions. In Sec. 3 we explore the contribution of isovector dibaryons (mainly the $\mathcal{D}_{12}(2150)$) to the one-pion production processes. By using the realistic parameters for dibaryon resonances, we obtain a good description for the $pp \rightarrow d\pi^+$ partial and total cross sections. We show further that the assumed values of dibaryon parameters do not lead to contradictions in theoretical description of the empirical data for pp and π^+d elastic scattering. Sec. 4 is devoted to the analysis of the different 2π -production processes in pn and pp collisions. The possibility of a consistent description for one- and two-pion production processes with inclusion of intermediate dibaryon resonances is demonstrated. In Sec. 5 we discuss the possible quark-cluster structure of dibaryons and its relation to the observed strong differences between the 2π production cross sections in pn and pp collisions in the GeV region. Finally, in Sec. 6 we briefly summarize our conclusions.

2. Conventional description of the one-pion production reaction $NN \rightarrow d\pi$: problems and solutions

The basic one-pion production reaction $NN \rightarrow d\pi$ has been the subject of very numerous experimental and theoretical studies since 1950ies (see

review [69]). The reaction was treated within the framework of phenomenological models [33, 70], the coupled-channels approach [29, 30] and also the Faddeev-type multiple-scattering approach [31, 32]. Thus it has long been revealed that the main features of the process at energies $T_N = 400\text{--}800$ MeV can be explained by excitation of an intermediate $N\Delta$ system. The important role is also played by interference of the $N\Delta$ mechanism with the one-nucleon-exchange process. From the other hand, the final-state rescattering contributions were estimated to give no more than 20% of the total cross section without changing the basic qualitative features of the reaction [33]. However, a number of more sensitive polarization characteristics were not reproduced within the framework of conventional meson-exchange models [32, 33]. So, it was claimed [24] that excitation of the intermediate dibaryon resonances found in elastic pp scattering [5, 9, 10] should be taken into account in the $NN \rightarrow d\pi$ process as well.

On the other hand, since one-pion production is accompanied by rather large momentum transfers ($\Delta p > 350$ MeV), the contribution of the conventional $N\Delta$ mechanism depends strongly on the short-range cut-off parameters in the πNN and $\pi N\Delta$ vertices [70]. Therefore, the proper choice of these parameters is crucial to determine the real contribution of the conventional mechanisms and the possible role of the intermediate dibaryon resonances. To our knowledge, this important problem, i.e., the relationship between the contributions of intermediate dibaryons and the values of the cut-off parameters $\Lambda_{\pi NN}$ and $\Lambda_{\pi N\Delta}$, has not been paid enough attention in the existing literature. However, clarification of this issue plays a key role in the present study. Therefore, after describing the basic formalism for the reaction $NN \rightarrow d\pi$, we consider this problem in detail.

2.1. Basic formalism

Two basic conventional mechanisms of the reaction $NN \rightarrow d\pi$, i.e., one-nucleon exchange¹ and excitation of the intermediate $N\Delta$ system by the t -channel pion exchange are shown in Fig. 1 (a) and (b), respectively. Further on, we will refer to these mechanisms as ONE and $N\Delta$. An excitation of the intermediate Δ isobar through the ρ -meson exchange was also often considered in the literature [70], but such a mechanism contributes significantly

¹The one-nucleon-exchange mechanism of the reaction $NN \rightarrow d\pi$ is often referred to in the literature as an impulse approximation [33, 70]. However, we prefer to imply under the impulse approximation its standard meaning, i.e., single scattering in elastic processes.

only when choosing very high cut-off parameters in the meson-baryon form factors. Here, we choose the soft values for the cut-off parameters² $\Lambda < 1$ GeV (reasons for this are given below), for which the contribution of the ρ -exchange mechanism is very small.

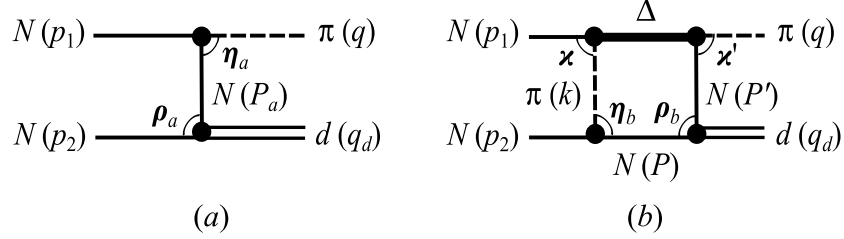


Figure 1: Diagrams illustrating two basic conventional mechanisms for the reaction $NN \rightarrow d\pi$: one-nucleon exchange (a) and intermediate Δ -isobar excitation (b). The 4-momenta of the particles are shown in parentheses, and 3-momenta in pair center-of-mass systems are denoted by bold face.

Relativistic helicity amplitudes corresponding to the diagrams depicted in Fig. 1 can be written as follows:

$$\mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}^{(\text{ONE})} = I_a (2m)^2 \sum_{\lambda'} [\bar{v}(p_2, \lambda_2) G_{dNN}(\lambda_d) u(P', \lambda')] \times \frac{1}{P'^2 - m^2 + i0} [\bar{u}(P', \lambda') F_{\pi NN} \gamma^\mu q_\mu \gamma_5 u(p_1, \lambda_1)], \quad (1)$$

$$\mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}^{(N\Delta)} = I_b (2m)^2 \sum_{\lambda, \lambda'} \int \frac{id^4 P}{(2\pi)^4} \frac{1}{k^2 - m_\pi^2 + i0} [\bar{v}(p_2, \lambda_2) F_{\pi NN} \gamma^\mu k_\mu \gamma_5 v(P, \lambda)] \times \frac{1}{P^2 - m^2 + i0} [\bar{v}(P, \lambda) G_{dNN}(\lambda_d) u(P', \lambda')] \frac{1}{P'^2 - m^2 + i0} \mathcal{M}_{\lambda', \lambda_1}^{(\pi N)}, \quad (2)$$

where $\mathcal{M}_{\lambda', \lambda_1}^{(\pi N)}$ is the πN -scattering amplitude via an intermediate Δ isobar:

$$\mathcal{M}_{\lambda', \lambda_1}^{(\pi N)} = -4m W_\Delta \bar{u}(P', \lambda') \frac{F'_{\pi N \Delta} q^\alpha \mathcal{P}_{\alpha\beta}^{(3/2)} k^\beta F_{\pi N \Delta}}{W_\Delta^2 - M_\Delta^2 + iW_\Delta \Gamma_\Delta(W_\Delta)} u(p_1, \lambda_1). \quad (3)$$

²In the present paper, we assume $\hbar = c = 1$, so the particle masses and momenta are measured in energy units.

The G_{dNN} in Eqs. (1) and (2) stands for the relativistic deuteron vertex, I_a and I_b are the isospin coefficients and $\mathcal{P}_{\alpha\beta}^{(3/2)}$ in Eq. (3) denotes the projection operator for the intermediate Δ . The nucleon spinors are normalized as $\bar{u}u = -\bar{v}v = 1$. The vertex form factors $F_{\pi NN}$ and $F_{\pi N\Delta}$ will be defined below.

Since not only the reaction amplitudes \mathcal{M} defined in Eqs. (1)–(3), but also each elementary amplitude (enclosed in square brackets in Eqs. (1) and (2)) are relativistically invariant, it is convenient to calculate each elementary amplitude in its own c.m.s. Then the resulted expressions for the amplitudes can be cast into a non-relativistic form, up to a some energy-dependent factor of relativistic nature. The explicit form of this factor depends on the specific choice of the relativistic vertex and often cannot be determined unambiguously, hence we assume all such factors to be unity. Neglecting also the small effects of relativistic spin rotations for the intermediate nucleons, we can write the total amplitude in terms of nonrelativistic vertices depending on the relative 3-momenta in pairs of particles. Finally, applying the standard approximation of the spectator nucleon [70]

$$\int \frac{id^4P}{(2\pi)^4} \frac{2m}{P^2 - m^2 + i0} \Big|_{P_0=\sqrt{\mathbf{P}^2+m^2}} \rightarrow \int \frac{d^3P}{(2\pi)^3} \quad (4)$$

and introducing the deuteron wavefunction (d.w.f.)

$$\bar{v}(P)G_{dNN}u(P')\frac{\sqrt{2m}}{P'^2 - m^2 + i0} \rightarrow -\chi^\dagger i\sigma_2 \Psi_d^*(\boldsymbol{\rho})\chi, \quad (5)$$

one gets the following expressions for the above amplitudes:

$$\mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}^{(\text{ONE})} = -I_a(2m)^{3/2}\chi^\dagger(\lambda_2)i\sigma_2\Psi_d^*(\boldsymbol{\rho}_a, \lambda_d)F_{\pi NN}(\eta_a)(\boldsymbol{\sigma}\boldsymbol{\eta}_a)\chi(\lambda_1), \quad (6)$$

$$\begin{aligned} \mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}^{(N\Delta)} &= -I_b(2m)^{1/2}\chi^\dagger(\lambda_2)i\sigma_2 \int \frac{d^3P}{(2\pi)^3} \frac{F_{\pi NN}(\eta_b)(\boldsymbol{\sigma}\boldsymbol{\eta}_b)}{w_\pi^2 - m_\pi^2 + i0} \\ &\times \Psi_d^*(\boldsymbol{\rho}_b, \lambda_d) \sqrt{\frac{\Gamma_\Delta(\boldsymbol{\varkappa})\Gamma_\Delta(\boldsymbol{\varkappa}')}{\boldsymbol{\varkappa}^3 \boldsymbol{\varkappa}'^3}} \frac{16\pi W_\Delta^2(\boldsymbol{\varkappa}\boldsymbol{\varkappa}' + i\frac{\boldsymbol{\sigma}}{2}\boldsymbol{\varkappa} \times \boldsymbol{\varkappa}')}{W_\Delta^2 - M_\Delta^2 + iW_\Delta\Gamma_\Delta(W_\Delta)} \chi(\lambda_1), \end{aligned} \quad (7)$$

where $w_\pi^2 = k^2$ and we used the relation of the Δ -isobar width to the vertex function $F_{\pi N\Delta}$:

$$\Gamma_\Delta(\boldsymbol{\varkappa}) = \frac{\boldsymbol{\varkappa}^3 m}{6\pi W_\Delta} F_{\pi N\Delta}^2(\boldsymbol{\varkappa}). \quad (8)$$

To calculate the spin structure of the amplitudes, it is convenient to write the d.w.f. in the form

$$\Psi_d(\boldsymbol{\rho}, \lambda_d) = \boldsymbol{\sigma} \mathbf{E}(\boldsymbol{\rho}, \lambda_d), \quad (9)$$

where we introduced the vector

$$\mathbf{E}(\boldsymbol{\rho}, \lambda_d) = u(\rho) \boldsymbol{\varepsilon}(\lambda_d) + \frac{w(\rho)}{\sqrt{2}} \left(\boldsymbol{\varepsilon}(\lambda_d) - \frac{3\boldsymbol{\rho}(\boldsymbol{\rho} \cdot \boldsymbol{\varepsilon}(\lambda_d))}{\rho^2} \right). \quad (10)$$

Here, $\boldsymbol{\varepsilon}(\lambda_d)$ is the standard deuteron polarization vector, u and w are the S - and D -wave components of the d.w.f. normalized as $\int d^3\rho (u^2 + w^2) / (2\pi)^3 = 1$.

Although the vertices in Eqs. (6) and (7) are calculated non-relativistically, we still employ relativistic kinematics in calculations of the relative momenta, according to the minimal relativity principle. In fact, comparison of the results of non-relativistic [70] and fully relativistic [33] calculations for the ONE and $N\Delta$ mechanisms shows that the account of relativistic effects as well as the deviation from the nucleon-spectator approximation give a correction of no more than 10–15%. Since the description of the $NN \rightarrow d\pi$ reaction in terms of two basic mechanisms only is initially approximate, the fully relativistic description of these mechanisms, requiring much more elaborated calculations, seems impractical at this stage. Furthermore, since the relativistic factors which we neglected here would increase the cross sections by 10–15% and the rescattering corrections would, on the contrary, decrease them by $\simeq 20\%$ [33], these two types of corrections would considerably cancel each other.

For definiteness, the reaction $pp \rightarrow d\pi^+$ will be considered further. Then the isospin coefficients are $I_a = \sqrt{2}$ and $I_b = 4\sqrt{2}/3$. The helicity amplitudes must be antisymmetrized over the initial protons. Then they take the form³ [33]

$$\mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}^{(s)}(\theta) = \mathcal{M}_{\lambda_1, \lambda_2; \lambda_d}(\theta) + (-1)^{\lambda_d} \mathcal{M}_{\lambda_2, \lambda_1; \lambda_d}(\pi - \theta). \quad (11)$$

Overall, there are 6 independent helicity amplitudes in the reaction $pp \rightarrow d\pi^+$:

$$\Phi_1 = \mathcal{M}_{\frac{1}{2}, \frac{1}{2}; 1}^{(s)}, \quad \Phi_2 = \mathcal{M}_{\frac{1}{2}, \frac{1}{2}; 0}^{(s)}, \quad \Phi_3 = \mathcal{M}_{\frac{1}{2}, \frac{1}{2}; -1}^{(s)},$$

³The factor $1/\sqrt{2}$ appearing in Eq. (A8) of Ref. [33] as well as the same factor for the d - n - p isospin vertex are included here in the d.w.f. normalization.

$$\Phi_4 = \mathcal{M}_{\frac{1}{2}, -\frac{1}{2}; 1}^{(s)}, \quad \Phi_5 = \mathcal{M}_{\frac{1}{2}, -\frac{1}{2}; 0}^{(s)}, \quad \Phi_6 = \mathcal{M}_{\frac{1}{2}, -\frac{1}{2}; -1}^{(s)}. \quad (12)$$

The total cross section is expressed through the above six amplitudes as follows:

$$\sigma(pp \rightarrow d\pi^+) = \frac{1}{64\pi s} \frac{q}{p} \int_{-1}^1 \sum_{i=1}^6 |\Phi_i(x)|^2 dx, \quad (13)$$

where p and q are the moduli of the proton and the pion c.m.s. momenta, respectively, and $x = \cos(\theta)$.

For comparison of the theoretical results with the PWA data and for studying the contributions of the intermediate dibaryon resonances, it is convenient to deal with the partial-wave amplitudes, which are expressed through the helicity ones via the standard formulas given by Jacob and Wick [71]. We display here the explicit formulas for the amplitudes in two dominant partial waves $^{2S+1}L_J L^{\pi d} = {}^1D_2 P$ and ${}^3F_3 D$ only:⁴

$$A({}^1D_2 P) = \frac{1}{2} \sqrt{\frac{3}{5}} \left(\Phi_1^{(2)} + \Phi_3^{(2)} \right) + \frac{1}{\sqrt{5}} \Phi_2^{(2)}, \quad (14)$$

$$A({}^3F_3 D) = -\frac{2}{\sqrt{7}} \Phi_4^{(3)} - \frac{1}{2} \sqrt{\frac{6}{7}} \Phi_5^{(3)}, \quad (15)$$

where

$$\Phi_i^{(J)} = \int_{-1}^1 d_{\lambda_1 - \lambda_2, -\lambda_d}^{(J)}(x) \Phi_i(x) dx. \quad (16)$$

The respective partial cross sections are

$$\sigma(^{2S+1}L_J L^{\pi d}) = \frac{(2J+1)}{64\pi s} \frac{q}{p} |A(^{2S+1}L_J L^{\pi d})|^2. \quad (17)$$

2.2. Parametrization of the vertex form factors: the cut-off problem

The main issue in the calculation of the amplitudes for the conventional processes, such as $N\Delta$ mechanism shown in Fig. 1 (b), is the parametrization of the meson-baryon vertex functions, in our case, the $F_{\pi NN}$ and $F_{\pi N\Delta}$,

⁴ S and L are related to the NN system.

especially in the short-range (or high-momentum) region. In fact, the exact form of these vertex functions and the true values for the short-range cut-off parameters $\Lambda_{\pi NN}$ and $\Lambda_{\pi N\Delta}$ are still unknown, despite the very numerous works dedicated to this problem (see, e.g., [72] and references therein). However, results of the different quark-model-based calculations agree, in general, that these parameters should be essentially soft ($\Lambda = 0.4\text{--}0.9$ GeV) [72].

In the present study, we have chosen the most simple vertex parametrization which follows directly from the basic principles of non-relativistic quantum mechanics combined with a minimal relativity principle. The advantages of such a choice are demonstrated below.

In the πN c.m.s., the vertex functions $F_{\pi NN}$ and $F_{\pi N\Delta}$ depend on the relative momentum of the pion and the nucleon. In its turn, the modulus of the relative momentum of two particles b and c produced in the decay of a particle a is a relativistically invariant quantity depending on invariant masses of all three particles:

$$p_{bc}^2 = \frac{(w_a^2 - w_b^2 - w_c^2)^2 - 4w_b^2 w_c^2}{4w_a^2}. \quad (18)$$

Then, writing the vertex form factor as a functions of p_{bc} makes it possible to describe *the real and virtual particles in a unified manner*.

When choosing a simple monopole parametrization for the above vertex functions, one has:

$$F_{\pi NN}(p, \tilde{\Lambda}) = \frac{f}{m_\pi} \frac{p_0^2 + \tilde{\Lambda}^2}{p^2 + \tilde{\Lambda}^2}, \quad (19)$$

$$F_{\pi N\Delta}(p, \tilde{\Lambda}_*) = \frac{f_*}{m_\pi} \frac{p_0^2 + \tilde{\Lambda}_*^2}{p^2 + \tilde{\Lambda}_*^2}, \quad (20)$$

where p^2 is a modulo squared of the π - N relative momentum (i.e., the pion momentum in the πN c.m.s.) and p_0^2 corresponds to the situation when all three particles are real, i.e., located on their mass shells. Then one gets the standard expression for the $\Delta \rightarrow \pi N$ decay width (see Eq. (8)):

$$\Gamma_\Delta(p) = \Gamma_\Delta \left(\frac{M_\Delta}{W_\Delta} \right) \left(\frac{p}{p_0} \right)^3 \left(\frac{p_0^2 + \tilde{\Lambda}_*^2}{p^2 + \tilde{\Lambda}_*^2} \right)^2. \quad (21)$$

The coupling constants in Eqs. (19)–(20) have been taken to be $f = 0.97$ and $f_* = 2.17$. In this case, one has $f^2/4\pi = 0.075$, and the above value for

f_* was derived from the total width of the Δ isobar $\Gamma_\Delta = 117$ MeV as given by the Particle Data Group [73].

In case when *only pion* is off the mass shell, Eqs. (19)–(20) are reduced to the standard monopole form factors, depending on the pion invariant mass w_π only (up to small terms proportional to w_π^4):

$$F_{\pi NN}(w_\pi; w_N = m, w_N = m) \simeq \frac{f}{m_\pi} \frac{m_\pi^2 - \Lambda^2}{w_\pi^2 - \Lambda^2}, \quad (22)$$

$$F_{\pi N\Delta}(w_\pi; w_N = m, w_\Delta = M_\Delta) \simeq \frac{f_*}{m_\pi} \frac{m_\pi^2 - \Lambda_*^2}{w_\pi^2 - \Lambda_*^2}, \quad (23)$$

where the cut-off parameters are related to the initial ones by

$$\Lambda^2 \simeq \tilde{\Lambda}^2, \quad \Lambda_*^2 \simeq \left(\tilde{\Lambda}_*^2 + \left(\frac{M_\Delta^2 - m^2}{2M_\Delta} \right)^2 \right) / \left(\frac{M_\Delta^2 + m^2}{2M_\Delta^2} \right). \quad (24)$$

It should be noted here that a different parametrization for the phenomenological vertices of the type $F_{a \rightarrow bc}$ is often used in the literature. In this commonly used parametrization, the total vertex function is represented as a product of three independent functions, each depending on the one invariant mass only (see, e.g., [74]). This form of the vertices contains at least three independent parameters, some of which cannot be found from experimental data. Therefore, such a parametrization does not allow to establish a direct interconnection between the different processes involving the same particles *on* and *off* the mass shell. On the other hand, the vertex parametrization of the form $F(p_{bc}, \Lambda)$ with a single cut-off parameter Λ , used in the present work, is consistent with the basic principles of quantum mechanics and admits a straightforward off-shell continuation. The parameter Λ in such a case can in general be found directly from experimental data.

Thus, the parameter $\tilde{\Lambda}_*$ in the $\pi N\Delta$ vertex can be found from empirical data on πN elastic scattering. Fig. 2 shows the PWA (SAID) data [75] for the πN -scattering cross section in the P_{33} partial wave and the results of calculations in the isobar model with a vertex form factor (20) for two values of the parameter $\tilde{\Lambda}_*$. We found that the best agreement between the theoretical calculation and the empirical data in a wide energy range is obtained by choosing the value $\tilde{\Lambda}_* = 0.3$ GeV.⁵ Then, using Eq. (24), we

⁵We note in passing that a similar value $\tilde{\Lambda}_* \simeq 0.36/\sqrt{2} \simeq 0.26$ GeV (where we used

obtain the respective monopole parameter $\Lambda_* = 0.44$ GeV, which is indeed very soft.

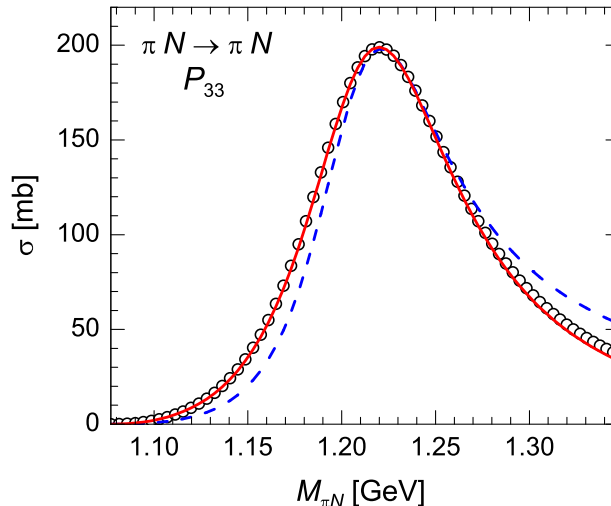


Figure 2: (Color online) The cross section of πN elastic scattering in the P_{33} partial wave. Solid and dashed lines show the calculations in the isobar model with the $\pi N\Delta$ vertex in the form (20) and the cut-off parameters $\tilde{\Lambda}_* = 0.3$ and 0.55 GeV, respectively. Solid circles correspond to the PWA data (SAID, solution WI08 [75]).

It was argued in a number of theoretical works that the cut-off parameter value in the $\pi N\Delta$ vertex (in the monopole form) should be substantially (100–300 MeV) less than that in the πNN vertex (see, e.g., [72, 77, 78]). In the present study, we have taken the value $\Lambda \simeq \tilde{\Lambda} = 0.7$ GeV, which was used in a number of previous calculations of reactions such as $NN \rightarrow d\pi$ [33, 79]. This value of Λ is consistent with the predictions of the lattice-QCD calculations [80, 81] (see also Ref. [82]). Thus, the monopole fits for the results obtained in [80] (lattice QCD with extrapolation to the physical pion mass) and [81] (extrapolation to the chiral limit) give $\Lambda = 0.75$ and 0.61 GeV, respectively. We emphasize here that the similar values $\Lambda = 0.65$ – 0.7 GeV were obtained in the fit of NN -scattering phase shifts and the deuteron properties within the dibaryon model for NN interaction [67]. One should

the relation of the monopole cut-off parameter to the dipole one) was taken in Ref. [76] to describe the NN -scattering phase shifts up to the energies $T_N = 2$ GeV consistently with πN elastic scattering.

also note that relativistic quark models predict an even softer cut-off for the πNN vertex function [82]. Unfortunately for the $\pi N\Delta$ form factor, we presently have no lattice-QCD predictions at the physical pion mass (or the respective extrapolation), and the available results at $m_\pi \simeq 300$ MeV [83] give too high cut-off parameters for both πNN and $\pi N\Delta$ vertices. Therefore, one is forced to use phenomenological parametrizations for $F_{\pi N\Delta}$, like the one used in this work, trying to relate the parameters to experimental data wherever possible.

So, for the ratio of the cut-off parameters in the vertices $F_{\pi NN}$ and $F_{\pi N\Delta}$, we obtained the value $\Lambda_*/\Lambda \simeq 0.6$. Note that the same value was derived in [84] from comparison of the relativistic meson-exchange model calculations with experimental data for the process $NN \rightarrow NN\pi$.

It should be stressed here once again that the parametrization for the vertex functions $F_{\pi NN}$ and $F_{\pi N\Delta}$ which we adopt in the present study describes the real and virtual particles in a unified manner. Hence, it can be used for consistent description of different processes involving on- and off-shell pions, i.e., $\pi N \rightarrow \pi N$, $NN \rightarrow \pi d$, elastic NN scattering, etc., with the same realistic (soft) cut-off parameters in the meson-baryon vertices. It does not require introducing any additional parameters to account for the pion virtuality. Although this choice of the vertex parametrization is not unique, it seems to be the simplest and most natural one.

It also should be stressed that the cut-off parameters used here are much softer than those traditionally used in the realistic NN -potential models. For example, in the Bonn model [85], the minimal values, which still allow a good description of NN -scattering phase shifts up to $T_N = 350$ MeV, are $\Lambda \simeq \Lambda_* \simeq 1.3$ GeV (in the upgraded CD-Bonn model [86] these values are even higher). Such very high cut-off parameters apparently lead to increased meson-exchange contributions at small inter-nucleon distances. In many cases, however, the artificial strengthening of the meson-exchange processes can mimic somehow the contributions of short-range QCD-based mechanisms which involve the quark-meson structure of interacting nucleons. So, in this way, the t -channel meson-exchange mechanisms with artificially enhanced cut-off parameters can really give the correct behaviour of some observables. For example, as was shown in Ref. [87], an accurate description of the basic deuteron properties can be obtained in the simple meson-exchange model, which takes into account the one-pion exchange only, without any cut-off, i.e., with $\Lambda = \infty$. One can suggest this continuity between the peripheral meson-exchange and short-range QCD-based mechanisms to be a

manifestation of a fundamental quark/hadron continuity principle.

On the other hand, from the fact that the vertex function $F_{\pi N\Delta}$ in πN scattering should have $\Lambda_* \simeq 0.4$ GeV, while for the description of reactions like $NN \rightarrow d\pi$ one should take $\Lambda_* \simeq 0.6$ GeV (see below and also Ref. [79]), and at the same time the correct description of the deuteron properties and S -wave NN -scattering requires $\Lambda_* \simeq 1.3$ GeV [85], it follows that the phenomenological approach based on *ad hoc* fitting the short-range cut-off parameters in the meson-baryon vertices to describe a specific process is not quite consistent, and probably contains some internal contradictions tightly related to the contributions of quark d.o.f. (see Ref. [88] for the detailed discussion on this issue). Instead, one could use the *universal* (essentially soft) cut-off parameters in the meson-baryon vertices to describe *different processes in a unified manner*. Then the deviations from experimental data, which would inevitably arise in this situation, might be regarded as indications of some short-range QCD-based mechanisms, not taken into account in the conventional meson-exchange approach. In this case, the stronger the observed discrepancies are and, accordingly, the larger cut-off parameters are needed to describe the experimental data, the stronger the “hidden” quark d.o.f. manifest themselves in the process in question. We will return to these ideas in Sec. 3, where the contributions of intermediate six-quark objects (dibaryons) will be considered.

As was shown above, the parametrization of the vertices in the form (19)–(20) allows us to take into account the effects of *any* of the three particles going off the mass shell. The most noticeable effect due to presence of the *off-shell nucleons* is seen in the ONE process, where the nucleon after pion emission is strongly off-shell. Introducing the form factor (19) at $(w_{N'}; w_\pi = m_\pi, w_N = m)$ in the vertex $F_{\pi NN'}$ (N' being the nucleon after pion emission), we found that the ONE contribution is reduced by $\simeq 30\%$ in comparison with the use of a constant $\pi NN'$ form factor. It should be noted that just the same effect was obtained in [33], where the vertex $F_{\pi NN'}$ with the off-shell nucleon has been derived from the dispersion relations. This coincidence provides an additional argument in favor of the vertex parametrization employed in the present work. We also got a reduction of the $N\Delta$ mechanism (taken in the nucleon-spectator approximation) due to the nucleon N' going off the mass shell, but this effect turned out to be less significant than in case of the ONE mechanism, and amounted to 10% only.

2.3. Results and discussion

We calculated the cross sections for the one-pion production reaction $pp \rightarrow d\pi^+$ in the energy range $\sqrt{s} = 2.03\text{--}2.27$ GeV ($T_p \simeq 320\text{--}860$ MeV) using the above formalism. The results for the partial cross section in the dominant partial wave 1D_2P and for the total cross section are shown in Fig. 3 (a) and (b), respectively. As “experimental” data for comparison with theoretical calculations, we took the results of PWA (SAID, solution C500 [89]) initially obtained for the inverse reaction $\pi^+d \rightarrow pp$. The cross sections of the two reactions are related as

$$\sigma(pp \rightarrow d\pi^+) = \frac{3}{2} \left(\frac{q}{p} \right)^2 \sigma(\pi^+d \rightarrow pp). \quad (25)$$

The advantage of the chosen PWA solution (C500) is that it was found in a combined analysis of the three interrelated processes $\pi^+d \rightarrow pp$, $pp \rightarrow pp$ and $\pi^+d \rightarrow \pi^+d$. The results of this PWA solution for the reaction $\pi^+d \rightarrow pp$ in the dominant partial waves 1D_2P , 3F_3D , etc., are in good agreement with the older PWA results [90, 91].

Because of the high transferred momenta in the one-pion production process ($\Delta p > 350$ MeV), the theoretical predictions can be expected to be sensitive to the model of the deuteron wave function (d.w.f.) used in calculations. To clarify this issue, we considered two models for the d.w.f. — the one derived from the CD-Bonn potential model [86] and the one obtained from the dibaryon model for NN interaction [68]. Both wave functions describe the observable deuteron properties well, but have different behaviour in the high-momentum region. Our study has shown that, although the ONE mechanism is indeed very sensitive to the choice of the d.w.f., the effect of using different d.w.f. models in the summed contribution of the ONE + $N\Delta$ mechanisms to the partial (1D_2P) and total cross sections does not exceed 10%. So, we present here the results for the dibaryon d.w.f. only.

We found that the conventional ONE + $N\Delta$ mechanisms with the meson-baryon vertices parameterized in the form (19)–(20) using the parameters $\tilde{\Lambda} = 0.7$ and $\tilde{\Lambda}_* = 0.3$ GeV (corresponding to the monopole parameters $\Lambda = 0.7$ and $\Lambda_* = 0.44$ GeV) give about half the experimental cross section in the 1D_2P partial wave and also about half the total cross section near their maximal values (at $\sqrt{s} \simeq 2.14\text{--}2.16$ GeV), with a theoretical peak shifted by about 20 MeV to the right relatively to its experimental position. It is worth noting that quite similar results were obtained previously in the works [24, 92].

On the other hand, due to the strong sensitivity of the results to the cut-off parameters in vertices $F_{\pi NN}$ and $F_{\pi N\Delta}$, enhancing these parameter values may lead to a significant increase in the theoretical cross sections. To demonstrate the importance of this observation, we examined two ways of the parameter variation. First, we increased the value of the parameter $\tilde{\Lambda}_*$ in the $\pi N\Delta$ vertex from 0.3 to 0.55 GeV. In this case, we were able to reproduce approximately the shape of both partial and total cross sections, however, with a significant shift of the resonance peak (see Fig. 3). On the other hand, as we demonstrated above, the value $\tilde{\Lambda}_* = 0.55$ GeV is no longer appropriate to describe the empirical data on the elastic πN scattering beyond the resonance peak (see Fig. 2).

The second way often used in the literature is changing the vertex parametrization itself, so that the degree of virtuality for each of the three particles is governed by its own cut-off parameter independent from other particles. In this case, the monopole form factors for the πNN and $\pi N\Delta$ vertices with off-shell pions (and an off-shell Δ) would be written as follows:

$$F_{\pi NN}^{(2)}(w_\pi) = \frac{f}{m_\pi} \frac{m_\pi^2 - \Lambda^2}{w_\pi^2 - \Lambda^2}, \quad (26)$$

$$F_{\pi N\Delta}^{(2)}(W_\Delta; w_\pi) = \frac{f_*}{m_\pi} \frac{\varkappa_0^2 + \tilde{\Lambda}_*^2}{\varkappa_{\text{on}}^2 + \tilde{\Lambda}_*^2} \frac{m_\pi^2 - \Lambda_*^2}{w_\pi^2 - \Lambda_*^2}, \quad (27)$$

where \varkappa_{on} is the magnitude of the on-shell π - N relative momentum, i.e., at $w_N = m$ and $w_\pi = m_\pi$, thus dependent on W_Δ only. In such a parametrization, the parameter $\tilde{\Lambda}_*$ can still be chosen as to describe the πN elastic scattering and thus should be equal to 0.3 GeV. The pion virtuality is, however, controlled by an additional parameter Λ_* , which cannot be determined from experimental data and thus is fitted to a particular process (in our case, $pp \rightarrow d\pi^+$). So, this way of vertex parametrization is fully *ad hoc*.

The results of calculations for the partial and total cross sections within the ONE + $N\Delta$ model using the vertex parametrization (26)–(27) are also shown in Fig. 3. It turns out that theoretical calculations are approximately consistent in magnitude with the empirical data, when using $\Lambda_* = 0.6$ GeV.

The dependence of the theoretically calculated value of the peak total cross section (at $\sqrt{s} = 2.16$ GeV) upon the cut-off parameters in vertices (parameterized in the form (26)–(27)) is shown in Fig. 4. In particular, the dependence of the peak cross section on the parameter Λ in the vertex $F_{\pi NN}$ at a fixed value of $\Lambda_* = 0.4$ GeV in the vertex $F_{\pi N\Delta}$ and the dependence

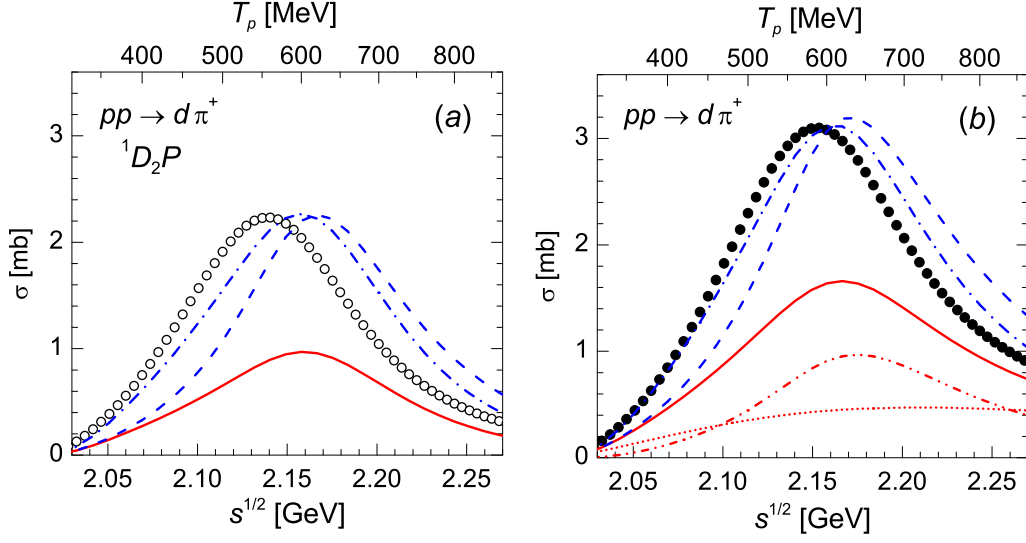


Figure 3: (Color online) (a) The partial $pp \rightarrow d\pi^+$ cross section in the dominant 1D_2P partial wave calculated within the ONE + $N\Delta$ model. Solid line — calculation with the vertex form factors (19)–(20) and parameter values $\tilde{\Lambda} = 0.7$ and $\tilde{\Lambda}_* = 0.3$ GeV, (corresponding to the monopole parameters $\Lambda = 0.7$ and $\Lambda_* = 0.44$ GeV — see Eq. (24)). Dashed line — the same vertex parametrization used but with $\tilde{\Lambda}_* = 0.55$ GeV (monopole $\Lambda_* = 0.68$ GeV). Dash-dotted line — calculation with form factors (26)–(27), $\Lambda = 0.7$ and $\Lambda_* = 0.6$ GeV. The open circles correspond to the PWA data (SAID, solution C500 [75, 89]). (b) The same as (a) but for the total $pp \rightarrow d\pi^+$ cross section. The individual contributions of the ONE and $N\Delta$ mechanisms are shown by dotted and dash-dot-dotted lines. The PWA results (coinciding with experimental data) are shown by filled circles.

on the parameter Λ_* at a fixed value of $\Lambda = 0.7$ GeV are presented. For comparison, the experimental peak cross section value (coincident with the PWA result) is also shown. It is seen from Fig. 4, that the theoretical cross section depends strongly on the cut-off parameters in vertices, especially on the parameter Λ_* in the $\pi N\Delta$ vertex. Thus, when Λ_* is increased by 50%, i.e., from 0.4 to 0.6 GeV, the cross section increases by two times.

So, when enhancing the cut-off parameters in vertices, one is able to approximately reproduce the experimental height of the cross section. However, as is seen from Fig. 3, independently on the vertex parametrization, the cross section peak remains shifted to the right relatively to its experimental position. This energy shift is particularly noticeable for the partial cross section in the 1D_2P wave, where it amounts to about 20–30 MeV. This result

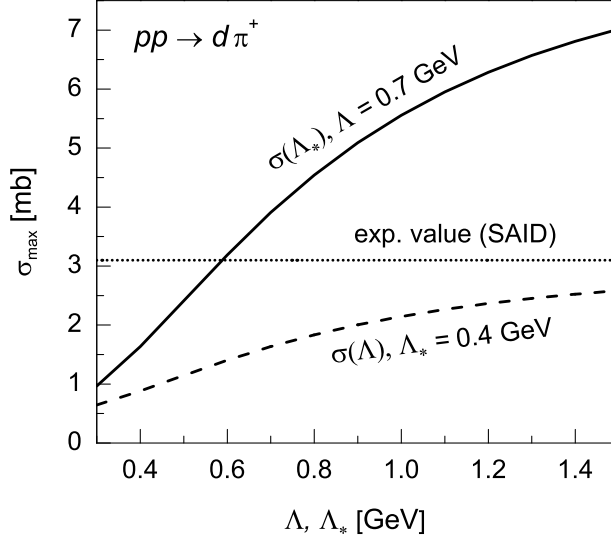


Figure 4: Dependence of the theoretically calculated total cross section for the reaction $pp \rightarrow d\pi^+$ at the peak ($\sqrt{s} = 2.16$ GeV) on the cut-off parameters in the vertices $F_{\pi NN}$ (Λ) and $F_{\pi N\Delta}$ (Λ_*) (see Eqs. (26)–(27)) is shown by dashed and solid lines, respectively. The empirical peak cross section (at $\sqrt{s} = 2.15$ GeV) according to PWA (SAID) data is shown by dotted line.

might be considered as an indication of the contribution of some additional mechanism in this process.

In particular, adding some $N\Delta$ attraction can shift the peak position of the calculated $pp \rightarrow d\pi^+$ cross section downwards (see, e.g., [93]). However, in view of the above problems with meson-baryon form factors and also the large width of the Δ , the nature of this attraction is not clear enough. We argue that generation of an intermediate dibaryon resonance may provide the basic attraction in the $N\Delta$ system (in addition to the peripheral pion exchange), similarly to that found in the NN system [67]. So, excitation of the intermediate dibaryon $\mathcal{D}_{12}(2150)$ in the 1D_2P partial wave seems to be a likely candidate for the missing mechanism. Indeed, according to the numerous predictions [17, 57, 61], the mass of this dibaryon lies about 10–30 MeV below the $N\Delta$ threshold. Besides that, although the discrepancies for the total cross section could in principle be eliminated by conventional mechanisms, significant disagreement with experimental data remains in the more sensitive spin-dependent observables, even after taking all rescattering

corrections (and also relativistic effects) into account. Particularly strong disagreement was revealed in the tensor analyzing powers [33, 32]. We postpone the detailed investigation of the observables (including spin-dependent ones) in the reaction $pp \rightarrow d\pi^+$ for our next paper. Here, we would just like to show that a consistent description of one-pion production by the conventional meson-exchange mechanisms encounters serious difficulties, including those which cannot be eliminated by fitting the cut-off parameters in the vertex form factors.

Thus, in this section we have demonstrated some problems faced by the conventional meson-exchange models in description of hadronic processes with high momentum transfers, in particular, of one-pion production. The main difficulty lies in the strong sensitivity to the short-range cut-off parameters in the vertices of meson emission and absorption. It is rather obvious that, until these parameters are determined accurately from the fundamental theory, one will not be able to reveal the real degree of discrepancy between the traditional meson-exchange model calculations and experimental data. Nevertheless, it appears to be a general trend that describing the processes involving two nucleons requires higher cut-off parameters in the meson-baryon vertices than the processes involving just one nucleon. Hence, instead of increasing the cut-off parameters *ad hoc* to describe the one-pion production (at the cost of consistency with other processes), one can try to find the missing contributions by including the resonance mechanisms based on the assumption of the intermediate dibaryon formation.

3. Inclusion of intermediate (isovector) dibaryons in one-pion production and elastic scattering

3.1. Reaction $pp \rightarrow d\pi^+$ with intermediate dibaryons

Let us now consider how the partial cross section of the reaction $pp \rightarrow d\pi^+$ in the dominant 1D_2P wave changes, if one adds to the background amplitude determined by the ONE + $N\Delta$ mechanisms (see Eq. (14)) the resonance amplitude corresponding to excitation of the intermediate dibaryon $\mathcal{D}_{12}(2150)$. A diagram illustrating such a resonance mechanism is shown in Fig. 5. The respective partial-wave amplitude has the form

$$A^{(D)}(^1D_2P) = -\frac{8\pi s}{\sqrt{pq}} \frac{\sqrt{2\Gamma_{D_{12} \rightarrow pp}(s) \Gamma_{D_{12} \rightarrow \pi d}(s)}}{s - M_{D_{12}}^2 + i\sqrt{s}\Gamma_{D_{12}}(s)}. \quad (28)$$

The factor 2 before the partial width $\Gamma_{D_{12} \rightarrow pp}$ is introduced to account for the identical particles in the initial state.

To calculate the contribution of an intermediate dibaryon to a particular process, one has to fix the dibaryon parameters somehow. It should be noted however that the parameters of dibaryon resonances and especially their partial widths are presently known with large uncertainties. The vast majority of phenomenological studies of dibaryon contributions to hadronic processes carried out in 1980ies (see, e.g., [24, 25, 27]) included *ad hoc* fitting the parameters of dibaryon resonances to a particular process in question. For instance, in the work [24] which considered dibaryon contributions to the process $pp \rightarrow d\pi^+$, the parameters of six hypothetical dibaryons were simultaneously fitted to describe the experimental data. So, it was highly uneasy to draw some reliable conclusions about the real contribution of intermediate dibaryons to this process. Contrary to this, we took reasonable values for the basic parameters of dibaryon resonances from existing literature or from the clear physical considerations, and then tested the sensitivity of the obtained results to the parameter variation. Presently, plausible estimates can be found in the literature at least for the most reliably established dibaryons $\mathcal{D}_{12}(2150)$ and $\mathcal{D}_{03}(2380)$.

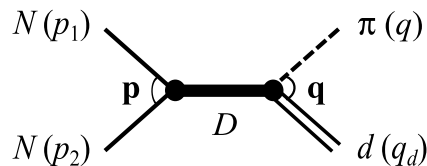


Figure 5: Diagram illustrating the excitation of an intermediate dibaryon resonance in the reaction $NN \rightarrow d\pi$.

For the dibaryon \mathcal{D}_{12} , we first fixed (up to ± 10 MeV) its mass and total width to be $M_{D_{12}} = 2.15$ GeV and $\Gamma_{D_{12}} = 110$ MeV. This choice was based on the PWA results [55, 56] and also on the results of the recent Faddeev calculations for the πNN system [61]. For parametrization of the energy dependence of the total resonance width, we took the form $\Gamma_{D_{12}}(s) = \Gamma_{D_{12} \rightarrow \pi d}(s)/R_{\pi d}$, where $R_{\pi d} = \Gamma_{D_{12} \rightarrow \pi d}/\Gamma_{D_{12}}$ is the branching ratio for the $\mathcal{D}_{12} \rightarrow \pi d$ decay mode at the resonance point. In other words, we assumed that the total width of the \mathcal{D}_{12} dibaryon is proportional to its partial decay width into the πd channel. This assumption was based on the fact that the decay $\mathcal{D}_{12} \rightarrow \pi NN$ has the same threshold behaviour and the same dynamical mechanism in its

origin as the decay $\mathcal{D}_{12} \rightarrow \pi d$, and the partial width $\Gamma_{\mathcal{D}_{12} \rightarrow NN}$, according to a number of estimates [7, 57], is only about 10% of the total dibaryon width. Although the final πNN channel has a different phase-space volume than the πd channel, however, in view of relatively weak influence of the energy dependence of the total resonance width on final results, we neglect this difference in the present calculation.

Further, for the partial width $\Gamma_{\mathcal{D}_{12} \rightarrow \pi d}$ we employed essentially the same parametrization as for the Δ -isobar width $\Gamma_{\Delta \rightarrow \pi N}$ (up to a factor M/W which is almost negligible for the dibaryon in the considered energy region):

$$\Gamma_{\mathcal{D}_{12} \rightarrow \pi d}(q) = \Gamma_{\mathcal{D}_{12} \rightarrow \pi d} \left(\frac{q}{q_0} \right)^3 \left(\frac{q_0^2 + \Lambda_{\pi d}^2}{q^2 + \Lambda_{\pi d}^2} \right)^2, \quad (29)$$

where q_0 is a value of the πd relative momentum q at the energy $\sqrt{s} = M_{\mathcal{D}_{12}} = 2.15$ GeV and $\Lambda_{\pi d} = \tilde{\Lambda}_* = 0.3$ GeV (cf. Eq. (21)). Given the fact that the basic hadronic component of the dibaryon \mathcal{D}_{12} is $N + \Delta$ [61], one may assume that the mechanism of the dibaryon decay at the quark level is essentially the same as that of the Δ decay, so the above choice seems to be quite natural. For the vertex $\mathcal{D}_{12} \rightarrow NN$, we used the Gaussian form factor derived on the basis of the quark shell model [67]. In the work [67], a fit was performed for the NN -scattering phase shifts up to the energies $T_N = 600$ MeV, within the framework of the dibaryon model for NN interaction. In its simplest form, the model included pion exchange at large NN distances and intermediate dibaryon (\mathcal{D}) formation at small distances. The authors [67] found the $\mathcal{D} \rightarrow NN$ vertex form factors in various NN partial waves in the form of projections of the six-quark wave functions onto the NN channel. In the quark shell model, such projections have the form of the harmonic oscillator wave functions. So, from the fit of the NN phase shift in the 1D_2 partial wave, the Gaussian (oscillator) form factor for the $\mathcal{D}_{12} \rightarrow NN$ vertex was obtained with a scale parameter $\alpha = 0.25$ GeV. In the present work, we took just this value as a first estimate.⁶ Thus, for the incoming width $\mathcal{D}_{12} \rightarrow NN$, we used the following parametrization:

$$\Gamma_{\mathcal{D}_{12} \rightarrow NN}(p) = \Gamma_{\mathcal{D}_{12} \rightarrow NN} \left(\frac{p}{p_0} \right)^5 \exp \left(-\frac{p^2 - p_0^2}{\alpha^2} \right), \quad (30)$$

⁶One should bear in mind that this value may be changed slightly, when one takes as a background to the dibaryon mechanism not only pion exchange with intermediate nucleon, but also pion exchange with intermediate Δ excitation.

where p_0 is a value of the NN relative momentum p at $\sqrt{s} = 2.15$ GeV.

As was mentioned above, the partial width $\Gamma_{D_{12} \rightarrow NN}$ is only $\simeq 10\%$ of the total width $\Gamma_{D_{12}}$, so, it is reasonable to assume $\Gamma_{D_{12} \rightarrow NN} = 10$ MeV. For the width $\Gamma_{D_{12} \rightarrow \pi d}$, there are various estimates in the literature. The most restrictive estimate $\Gamma_{D_{12} \rightarrow \pi d} / \Gamma_{D_{12}} \lesssim 0.1$ was obtained from the theoretical analysis of $\pi^+ d$ elastic scattering in the Δ region in several independent works [28, 26]. Given the high inelasticity of the \mathcal{D}_{12} dibaryon in the NN channel, it seems natural to assume the $\Gamma_{D_{12} \rightarrow \pi d}$ width to be not less than the $\Gamma_{D_{12} \rightarrow NN}$ one. So, for the present calculation, we have taken the value $\Gamma_{D_{12} \rightarrow \pi d} \simeq 0.1 \Gamma_{D_{12}} \simeq \Gamma_{D_{12} \rightarrow NN} = 10$ MeV.

Now it remains to determine the relative phase φ_{12} between the resonance amplitude of the \mathcal{D}_{12} excitation and the “background” amplitude given by $ONE + N\Delta$ mechanisms. Since we found the background processes to give a strong underestimation of the $pp \rightarrow d\pi^+$ cross section (see Fig. 3), it is natural first to consider the case $\varphi_{12} = 0$, corresponding to constructive interference between the resonance and background contributions. In fact, it turns out that for the above choice of dibaryon parameters, the phase $\varphi_{12} \simeq 0$ gives the best description of the data (from the best fit to PWA data, we have got $\varphi_{12} = 0.04$).

The results of calculation for the $pp \rightarrow d\pi^+$ partial cross section in the 1D_2P wave with the above fixed dibaryon parameters (summarized in set A of Table I) and the relative resonance/background phase $\varphi_{12} = 0$ are shown in Fig. 6 by thick solid line. We see that the theoretical curve is in very good agreement with the PWA data at all energies from threshold up to $\sqrt{s} \simeq 2.3$ GeV. It is important to emphasize that this result was obtained *without actual fit of free parameters* for both interfering amplitudes, i.e., the resonance and background ones.

Table 1: Parameters of dibaryon resonance \mathcal{D}_{12} (in MeV) used in calculations of the one-pion production reaction $pp \rightarrow d\pi^+$.

	$M_{D_{12}}$	$\Gamma_{D_{12}}$	$\Gamma_{D_{12} \rightarrow pp}$	α	$\Gamma_{D_{12} \rightarrow \pi d}$	$\Lambda_{\pi d}$
Set A (initial)	2150	110	10	250	10	300
Set B (modified)	2155	103	10	230	8.4	250

At the same time, we found that already a small change in the basic dibaryon parameters is sufficient to describe the partial 1D_2P cross section almost perfectly (i.e., in full agreement with the PWA data), with the same relative phase between the resonance and background amplitudes $\varphi_{12} = 0$.

These slightly modified parameters are presented in set B of Table I. In fact, to accurately describe the partial cross section near the resonance peak, one needs only to increase the dibaryon mass by 5 MeV, while the modification of other parameters improves mainly the description of the data at higher energies. The result of calculations with such slightly modified parameters is shown in Fig. 6 by thin solid line.

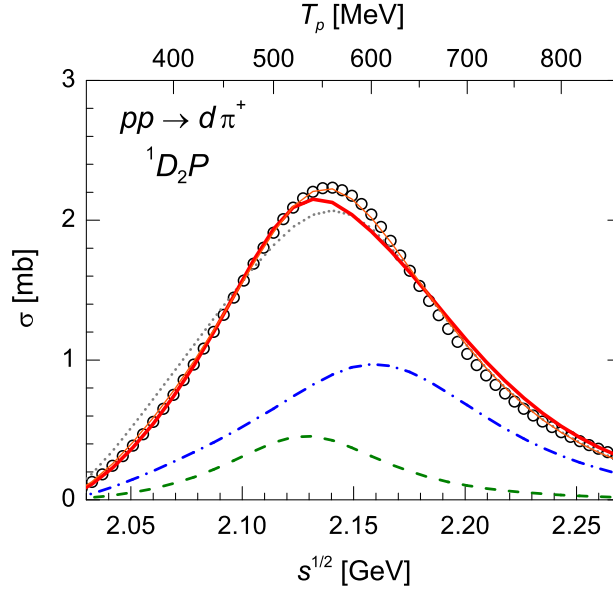


Figure 6: (Color online) Partial cross section of the reaction $pp \rightarrow d\pi^+$ in the 1D_2P channel. The results of calculation including the conventional ONE + $N\Delta$ mechanisms and an intermediate dibaryon excitation with the parameter set A (see Table I), i.e., with no actual fit, is shown by thick solid line. The individual contributions of the dibaryon excitation (dashed line) and background (ONE + $N\Delta$) processes (dash-dotted line) are also shown. The dotted line corresponds to the calculation with a reduced parameter $\Lambda_{\pi d} = 0.15$ GeV. The thin solid line shows the results obtained with slightly modified parameters of the dibaryon mechanism (see Table I, set B). Open circles correspond to the PWA data (SAID, solution C500 [75, 89]).

Furthermore, we found that the sensitivity of the results to the dibaryon mass and width is stronger than to the cut-off parameters in partial widths. However, the deviation of the latter parameters from the initially adopted values worsens (though not considerably) the description of the PWA data. For illustration, we have shown in Fig. 6 also the result of the calculation with

the reduced value $\Lambda_{\pi d} = 0.15$ GeV (this value corresponds to an assumption of a constant partial width near the resonance point). Therefore, an accurate description of the data requires “fine tuning” of the model parameters. Given this fact, it may seem surprising that, by choosing the parameters from the independent sources and making no actual fit, we have got a very good agreement with empirical data. On the other hand, if the parameter values used here are close to the real ones, then this result becomes quite natural.

Let us now consider the 3F_3D partial wave which also gives a significant contribution to the $pp \rightarrow d\pi^+$ cross section. The results of calculations for the 3F_3D partial cross section are shown in Fig. 7. Here the conventional ONE + $N\Delta$ mechanisms with soft cut-off parameters in meson-baryon vertices (see the previous section) also give about 40% of the partial cross section. An additional contribution can come from a next (after \mathcal{D}_{12}) member of the isovector dibaryon series, which is usually denoted as ${}^3F_3(2220)$ (we also will denote it as \mathcal{D}_{13}^- , following the notations of Ref. [17]). This dibaryon has quantum numbers $I(J^P) = 1(3^-)$, mass $M_{\mathcal{D}_{13}^-} \simeq 2200\text{--}2250$ MeV and total width $\Gamma_{\mathcal{D}_{13}^-} \simeq 100\text{--}200$ MeV [5, 94]. It was investigated in a number of works (see, e.g., [53, 95, 96], and it fits well into the classification of isovector dibaryons as a rotational band for the six-quark system clustered as $[q^4 - q^2]$ [19, 20] (see also Sec. 5).

We parameterized the amplitude corresponding to the \mathcal{D}_{13}^- resonance excitation and its total and partial widths in a similar way as for the \mathcal{D}_{12} resonance (see Eqs. (28)–(30)), with an apparent modification due to different angular momenta. When adding coherently the mechanism of the \mathcal{D}_{13}^- excitation to the summed background (ONE + $N\Delta$) contribution, one gets a very good description of the 3F_3D partial cross section. However, as the parameters of the \mathcal{D}_{13}^- dibaryon are known with larger uncertainties than those of the \mathcal{D}_{12} , they cannot be fixed a priori and still need to be fitted. The results shown in Fig. 7 were obtained with the following set of dibaryon parameters: $M_{\mathcal{D}_{13}^-} = 2200$ MeV, $\Gamma_{\mathcal{D}_{13}^-} = 140$ MeV, $\Gamma_{D13^- \rightarrow pp} \Gamma_{D13^- \rightarrow \pi d} = 3.5 \times 10^{-5}$ GeV², $\alpha({}^3F_3) = 0.26$ GeV, $\Lambda_{\pi d} = 0.3$ GeV. These parameters are consistent with estimates given in the literature. The relative phase between resonance and background amplitudes was again fixed to be zero.

Fig. 8 shows the total $pp \rightarrow d\pi^+$ cross section, calculated with and without intermediate dibaryons excitation taken into account. Here, in order to estimate the contribution of other partial waves, except for the dominant one 1D_2P , we used the set of parameters for the dibaryon mechanism, which

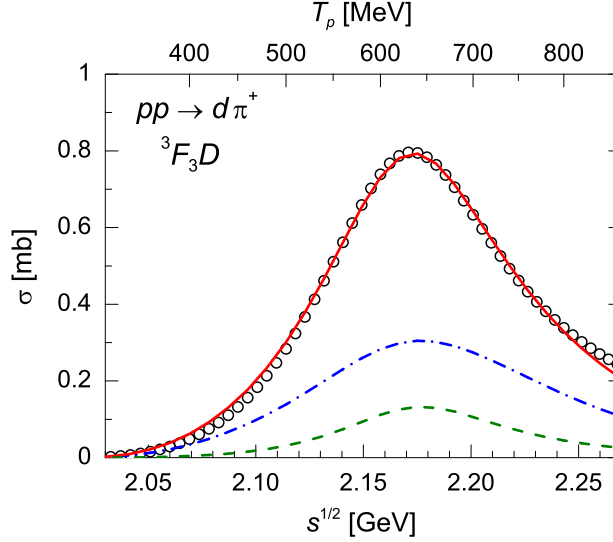


Figure 7: (Color online) Partial cross section of the reaction $pp \rightarrow d\pi^+$ in the 3F_3D channel. The summed contribution of the conventional ONE + $N\Delta$ mechanisms (dash-dotted line), the contribution of the dibaryon resonance \mathcal{D}_{13}^- (dashed line) and the full calculation including both mechanisms (solid line) are shown. Open circles correspond to the PWA data (SAID, solution C500 [75, 89]).

gives an accurate reproduction of the partial 1D_2P cross section (set B in Table I). It is seen from Fig. 8 that the background processes yield approximately half of the total cross section (the result already given in Sec. 2). When the dibaryon \mathcal{D}_{12} excitation mechanism is included in the calculation, the theoretical results are already in a good agreement with experimental data at low energies. However, at the energies close to the cross section peak and above there are still quite visible discrepancies.

Further, when adding both \mathcal{D}_{12} and \mathcal{D}_{13}^- resonance contributions to the background (ONE + $N\Delta$) mechanisms, the total $pp \rightarrow d\pi^+$ cross section is described well also at higher energies (see the thick solid line in Fig. 8). It is worth noting that including just these two resonances allowed previously to considerably improve the description of experimental data also for the reactions $pp \rightarrow pn\pi^+$ and $pp \rightarrow pp\pi^0$ [98].

So, for one-pion production reaction $pp \rightarrow d\pi^+$, we have shown that two lowest (by far dominant) partial waves, where large contributions from intermediate dibaryons might be expected, are described by our model very well

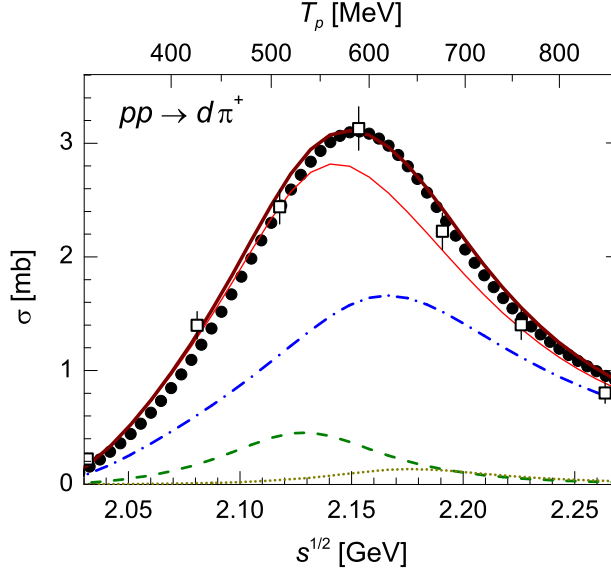


Figure 8: (Color online) Total cross section of the reaction $pp \rightarrow d\pi^+$ with account of the dibaryon resonance in the 1D_2P partial wave (thin solid line), as well as with two dibaryon resonances in the 1D_2P and 3F_3D partial waves included (thick solid line) in comparison with experimental data [97] (open squares) and the PWA data (SAID, solution C500 [75, 89]) (filled circles). The individual contributions of dibaryons in 1D_2P and 3F_3D partial waves are shown by dashed and dotted lines, respectively, and the summed contribution of two conventional processes $ONE + N\Delta$ is shown by dash-dotted line.

in a broad energy range. This result is sufficient for the main objective of the present study, i.e., to make conclusions about the relative contributions of dibaryon resonances and background t -channel processes. On the other hand, as is well known, the polarization observables (and even the differential cross section) are determined by not only the lowest partial waves, but also by the high partial waves which give a small ($< 10\%$) contribution to the total cross section. To describe well these high partial-wave amplitudes, which are governed basically by the peripheral t -channel processes, one needs a very accurate theoretical model for these processes. Since even the model based on solving the exact Faddeev-type equations [32] contains ambiguities which affect strongly the description of observables (e.g., due to account of small πN partial-wave amplitudes, treatment of the off-shell πN amplitude, etc.), here we do not claim the accurate description of the high partial waves. The detailed calculation of differential observables and comparison

with experimental data is a subject of our subsequent study.

Our final remark here concerns dibaryon resonances in higher NN partial waves 1G_4 , 3H_5 , etc., which can only be seen in particularly sensitive spin-dependent observables (such as the spin-correlation parameter C_{LL} in elastic pp scattering [5]). To study the contributions of such highly-excited dibaryons to the processes like $pp \rightarrow d\pi^+$, a very accurate description of the background reaction mechanisms is also required. It seems hardly possible even in a rigorous multiple-scattering approach, when keeping in mind the vertex form factors dependence described above.

On the other hand, an appealing opportunity to study these higher-lying dibaryon resonances is to find such processes where the relative contributions of background mechanisms at respective energies are even smaller than in one-pion production. Below, in Sec. 4, we consider the *two-pion production* reactions at intermediate energies from this viewpoint. Before that, however, it is important to study the dibaryon contributions (with the same parameters used here to describe one-pion production) to elastic NN and πd scattering.

3.2. Dibaryon contributions to elastic NN and πd scattering

It is generally known that the overall contribution of short-range QCD mechanisms to elastic scattering processes is very small, because elastic scattering occurs mainly in peripheral region and involves the short-range dynamics only weakly. On the other hand, when considering large-angle scattering, accompanied by high momentum transfers, one is likely to see the enhanced manifestation of quark d.o.f., in particular, the dibaryon resonances excitation. Indeed, there are numerous indications of this fact in the literature (see, e.g., [95, 96], and also [99, 100]). However, in the present paper, we restrict our analysis to the energy dependence of the partial and total cross sections only.

First of all, let us consider the pure contribution of the dibaryon \mathcal{D}_{12} excitation to the cross sections of pp and π^+d elastic scattering in partial waves 1D_2 and 3P_2 , respectively. The 1D_2 partial-wave amplitude for pp elastic scattering via the intermediate dibaryon \mathcal{D}_{12} has the form:

$$A_{pp}^{(D)}(^1D_2) = -\frac{8\pi s}{p} \frac{\sqrt{2}\Gamma_{D_{12} \rightarrow pp}(s)}{s - M_{D_{12}}^2 + i\sqrt{s}\Gamma_{D_{12}}(s)} \quad (31)$$

and the respective cross section is

$$\sigma_{pp}^{(D)}(^1D_2) = \frac{5}{64\pi s} |A_{pp}^{(D)}(^1D_2)|^2. \quad (32)$$

Similarly, for the 3P_2 partial-wave amplitude and cross section in πd elastic scattering one gets:

$$A_{\pi d}^{(D)}(^3P_2) = -\frac{8\pi s}{q} \frac{\Gamma_{D_{12} \rightarrow \pi d}(s)}{s - M_{D_{12}}^2 + i\sqrt{s}\Gamma_{D_{12}}(s)} \quad (33)$$

and

$$\sigma_{\pi d}^{(D)}(^3P_2) = \frac{5}{48\pi s} |A_{\pi d}^{(D)}(^3P_2)|^2. \quad (34)$$

Fig. 9 (a) shows that the dibaryon contribution to the 1D_2 partial cross section of elastic pp scattering is $\simeq 25\%$ at energies near the resonance peak. However, as the contribution of the 1D_2 partial wave itself is only 10% of the total elastic pp cross section, the D_{12} dibaryon contribution to the total elastic cross section will be 2.5% only. It is interesting to note that the qualitative behavior of the dibaryon contribution agrees well with the behavior of the empirical pp cross section in the 1D_2 partial wave. This is not unexpected, since we used for the $D_{12} \rightarrow NN$ vertex the Gaussian form factor obtained from fitting the 1D_2 NN -scattering phase shift within the dibaryon model [67]. On the other hand, it is known that the description of this phase shift within the framework of conventional meson-exchange models faces a number of problems. In particular, it requires the introduction of phenomenological L^2 -dependent terms in the NN potential (see, e.g., [101]). Looking at Fig. 9 (a), one may suppose that, when adding the dibaryon contribution to a relatively smooth background given by meson-exchange mechanisms (with soft form factors), one will obtain qualitatively correct behavior of the pp -scattering cross section in the 1D_2 partial wave.

Fig. 9 (b) shows the partial cross section of elastic $\pi^+ d$ scattering in the 3P_2 wave. An analysis of just this reaction in its time put the existence of isovector dibaryon resonances under question, when it became clear that the main features of experimental data can be explained in terms of the so-called “pseudoresonances”, appearing due to an intermediate $N + \Delta$ excitation [28]. The estimate for the dibaryon partial width $\Gamma_{D_{12} \rightarrow \pi d} \lesssim 0.1 \Gamma_{D_{12}}$ used in the present work was also obtained from the analysis of elastic $\pi^+ d$ scattering [26, 28]. Our results confirm that the dibaryon contribution (with

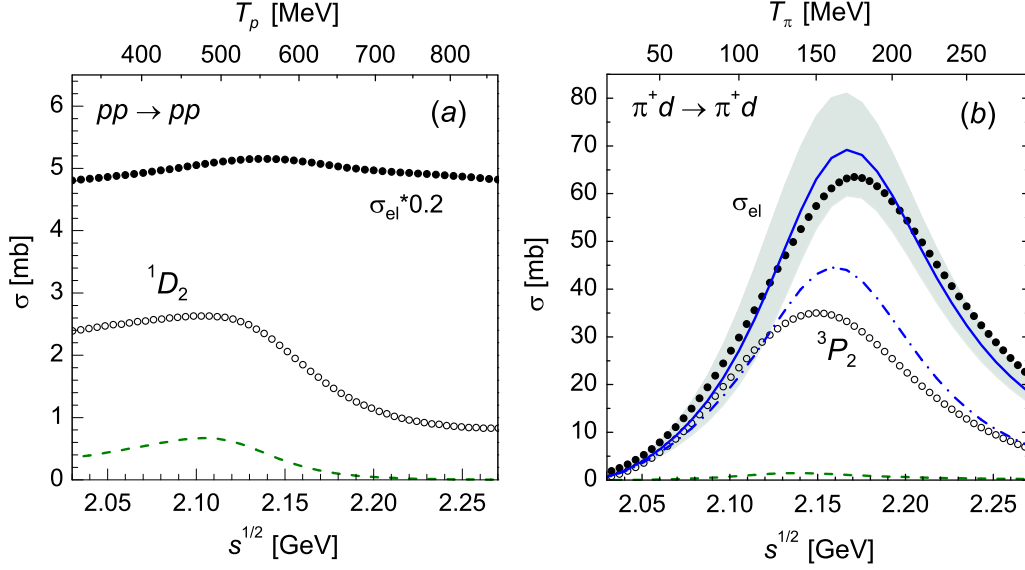


Figure 9: (Color online) Cross sections for pp (a) and π^+d (b) elastic scattering. The dashed lines correspond to contributions of the intermediate dibaryon \mathcal{D}_{12} excitation. The open circles show the PWA (SAID [75]) data for the cross sections in pp 1D_2 (solution SP07) and π^+d 3P_2 (solution C500) partial waves, and the filled circles show the respective data for the total elastic cross sections. The PWA data for the pp total elastic cross section are multiplied by a factor 0.2. For π^+d scattering, the dominant contributions of the single π^+N -scattering mechanism to the partial 3P_2 (dot-dashed line) and the total elastic (solid line) cross sections are also shown. The shaded area corresponds to the total elastic π^+d cross section resulting from the coherent superposition of the single scattering and dibaryon excitation mechanisms with an arbitrary relative phase.

the same parameters as were used to describe one-pion production) to elastic π^+d scattering even in the 3P_2 partial wave is indeed very small ($\simeq 5\%$). Further, since the 3P_2 partial wave gives about half total elastic π^+d cross section near its peak, we obtain the dibaryon contribution to the total elastic π^+d cross section to be about 2.5% only, similarly to the case of pp elastic scattering.

We calculated also the contribution of the standard single π^+N -scattering mechanism via an intermediate Δ -isobar excitation to the partial and total elastic π^+d cross sections. It is important to stress here that this mechanism, unlike the similar mechanisms of the intermediate Δ excitation in the $pp \rightarrow d\pi^+$ reaction and in pp elastic scattering, is very weakly dependent on the

cut-off parameter in the $\pi N\Delta$ vertex, because such vertices here contain the real pions only, and presence of virtual nucleons produces a very small effect on the cross sections.

The single-scattering amplitude in the nucleon-spectator approximation (see Eq. 4) is written as follows:

$$\begin{aligned} \mathcal{M}_{\lambda_d, \lambda'_d}^{(\text{SS})} = & -\frac{4}{3} \text{Sp} \int \frac{d^3\mathbf{P}}{(2\pi)^3} \Psi_d^*(\boldsymbol{\rho}_b, \lambda'_d) \sqrt{\frac{\Gamma_\Delta(\boldsymbol{\kappa})\Gamma_\Delta(\boldsymbol{\kappa}')}{\boldsymbol{\kappa}^3 \boldsymbol{\kappa}'^3}} \\ & \times \frac{16\pi W_\Delta^2(\boldsymbol{\kappa}\boldsymbol{\kappa}' + i\frac{\boldsymbol{\sigma}}{2}\boldsymbol{\kappa} \times \boldsymbol{\kappa}')}{W_\Delta^2 - M_\Delta^2 + iW_\Delta\Gamma_\Delta(W_\Delta)} \Psi_d(\boldsymbol{\eta}_b, \lambda_d), \end{aligned} \quad (35)$$

where the momenta are denoted as in Fig. 1 (b) (with the nucleon 1 and the virtual pion interchanged and the nucleon 2 replaced by the incoming deuteron) and the d.w.f. Ψ_d is given by Eqs. (9)–(10). There are four independent helicity amplitudes in πd elastic scattering:⁷

$$\Phi_1 = \mathcal{M}_{1,1}, \quad \Phi_2 = \mathcal{M}_{1,0}, \quad \Phi_3 = \mathcal{M}_{1,-1}, \quad \Phi_4 = \mathcal{M}_{0,0}. \quad (36)$$

Then one has for the total cross section

$$\begin{aligned} \sigma(\pi^+ d) = & \frac{1}{96\pi s} \int_{-1}^1 \left[2(|\Phi_1(x)|^2 + |\Phi_3(x)|^2) \right. \\ & \left. + 4|\Phi_2(x)|^2 + |\Phi_4(x)|^2 \right] dx, \quad x = \cos(\theta). \end{aligned} \quad (37)$$

The amplitude in the 3P_2 partial wave is expressed through the helicity amplitudes as

$$A(^3P_2) = \frac{3}{10} \left(\Phi_1^{(2)} + \Phi_3^{(2)} \right) + \frac{2\sqrt{3}}{5} \Phi_2^{(2)} + \frac{1}{5} \Phi_4^{(2)}, \quad (38)$$

where

$$\Phi_i^{(J)} = \int_{-1}^1 d_{\lambda_d, \lambda'_d}^{(J)}(x) \Phi_i(x) dx. \quad (39)$$

⁷We use here the same letters to denote the helicity and partial-wave amplitudes as for the $pp \rightarrow d\pi^+$ process since this should not lead to confusion.

Our calculations have shown, in agreement with results of many previous works [28, 26, 102], that the single-scattering mechanism gives the by far dominating contribution to the π^+d elastic cross sections, both partial and total. We found also that possible interference between the dibaryon and single-scattering contributions can give a scatter $\pm 12\%$ (depending on a relative phase) in the total elastic π^+d cross section, while the cross section shape, after adding the dibaryon contribution, remains practically unchanged (see Fig. 9 (b)). One should further take into account that the contribution of multiple scattering processes to the elastic π^+d cross section is $\simeq 20\%$ [103], which is significantly higher than that of the dibaryon mechanism. As a result, the effect of intermediate dibaryon excitation appears to be hardly visible in the total elastic cross sections of pp and π^+d scattering.

Thus, one can conclude from the above analysis that the model which includes the background (or pseudoresonance) meson-exchange processes and the intermediate dibaryon excitation mechanisms with reasonable parameters allows a good description of the one-pion production reaction $NN \rightarrow d\pi$ in a wide energy range and at the same time does not contradict the empirical data for elastic NN and πd scattering. One should however bear in mind the strong parameter dependence of such a model description, especially in the background t -channel mechanisms. In the next section we consider more clear manifestations of intermediate dibaryon resonances in the two-pion production processes, where the conventional meson-exchange contributions are expected to be smaller than those in one-pion production, due to the higher momentum transfers.

4. Dibaryon resonances in two-pion production

4.1. Reaction $pn \rightarrow d(\pi\pi)_0$: isoscalar/isovector transition

In reactions of two-pion production, where the initial NN pair merges into the final deuteron, there are two possible assignments for the total isospin $I = 1$ and 0 . The most interesting case is a purely isoscalar process $pn \rightarrow d(\pi\pi)_{I=0}$, where the famous ABC effect [44, 45], i.e., a strong enhancement in the yield of pion pairs near the 2π threshold, was observed [39] (see also an older inclusive experiment [104]). In recent works of the CELSIUS/WASA and then WASA@COSY Collaborations [39, 40] the ABC effect was associated with generation of a dibaryon resonance $\mathcal{D}_{03}(2380)$ with $I(J^P) = 0(3^+)$, originally predicted by Dyson and Xuong [17] and then studied in many theoretical and experimental works (see, e.g., [14, 15, 105, 106, 107, 52]). In

fact, it is the only isoscalar dibaryon resonance (except for the deuteron [17]) reliably established for today. The authors [40] found that the total cross section of the 2π -production reaction $pn \rightarrow d\pi^0\pi^0$ in the energy range $T_p = 1\text{--}1.2$ GeV is predominantly determined by excitation of the intermediate \mathcal{D}_{03} resonance, while the contribution of background processes (mainly excitation of an intermediate Δ - Δ state via a t -channel meson exchange [108]) is relatively small and does not exceed 10% near the cross section maximum (at $\sqrt{s} = 2.38$ GeV or $T_p = 1.14$ GeV). Therefore, the calculations of the 2π -production reactions in the isoscalar NN channel based on \mathcal{D}_{03} -resonance excitation only (i.e., without inclusion of the t -channel background processes) can be regarded as a good approximation, at least near the resonance peak.

In our previous work [51], we considered two decay modes for the resonance $\mathcal{D}_{03}(2380)$ into the $d\pi\pi$ channel, which follow directly from the dibaryon model for NN interaction [109]: (i) through emission of a light scalar σ meson and (ii) via an intermediate state $\mathcal{D}_{12}(2150) + \pi$. In other words, we assumed that while the isovector dibaryons cannot be excited directly in the isoscalar NN collisions, these dibaryons may be produced in the intermediate subsystem πNN , i.e., after the one-pion emission. Now we can verify this assumption independently, comparing the parameters of the isovector dibaryon \mathcal{D}_{12} in one- and two-pion production processes. We actually used in the present paper the same values for the \mathcal{D}_{12} mass and width, as in the previous calculations of 2π production [51]. However, the cut-off parameter $\Lambda_{\pi d}$ in the partial decay width $\mathcal{D}_{12} \rightarrow \pi d$ was chosen here to be 0.3 GeV, while in [51] the smaller value 0.15 GeV was used. As was shown above, the last value of $\Lambda_{\pi d}$ leads to a slight disagreement with the empirical data for the one-pion production at low energies (see Fig. 6), though due to uncertainties in our calculation for background processes, this discrepancy can hardly be considered to be significant. Below we will test the sensitivity of the 2π -production cross sections to the value of $\Lambda_{\pi d}$.

In the dibaryon model for 2π production [51], the amplitude for the reaction $pn \rightarrow d\pi^0\pi^0$ can be written as follows:

$$\mathcal{M}_{\lambda_p, \lambda_n, \lambda_d} = \frac{\sum_{\lambda_3} \mathcal{M}_{\lambda_p, \lambda_n, \lambda_3}^{(D_{03})} \left[\mathcal{M}_{\lambda_3, \lambda_d}^{(\sigma)} + \mathcal{M}_{\lambda_3, \lambda_d}^{(D_{12})} \right]}{s - M_{D_{03}}^2 + i\sqrt{s}\Gamma_{D_{03}}(s)}. \quad (40)$$

When choosing the z axis to be parallel to the initial c.m. momentum \mathbf{p} , the

dibaryon \mathcal{D}_{03} formation amplitude takes the form

$$\mathcal{M}_{\lambda_p, \lambda_n, \lambda_3}^{(D_{03})} = \sqrt{5} p^2 F_{pn \rightarrow D_{03}} C_{1\lambda_3 20}^{3\lambda_3} C_{\frac{1}{2}\lambda_p \frac{1}{2}\lambda_n}^{1\lambda_3}, \quad (41)$$

$C_{s_1 \lambda_1 s_2 \lambda_2}^{J\Lambda}$ being the Clebsch–Gordan coefficients. In its turn, for the dibaryon decay amplitudes, one gets the following expressions:

$$\begin{aligned} \mathcal{M}_{\lambda_3, \lambda_d}^{(\sigma)} &= \frac{F_{D_{03} \rightarrow d\sigma} F_{\sigma \rightarrow \pi\pi}}{M_{\pi\pi}^2 - m_\sigma^2 + iM_{\pi\pi} \Gamma_{D_{03}}(M_{\pi\pi}^2)} C_{1\lambda_d 2\mu}^{3\lambda_3} \mathcal{Y}_{2\mu}(\mathbf{p}_d, \mathbf{p}_d), \\ \mathcal{M}_{\lambda_3, \lambda_d}^{(D_{12})} &= \sqrt{\frac{6}{5}} \frac{F_{D_{03} \rightarrow D_{12}\pi_1} F_{D_{12} \rightarrow d\pi_2}}{M_{d\pi_2}^2 - M_{D_{12}}^2 + iM_{d\pi_2} \Gamma_{D_{12}}(M_{d\pi_2}^2)} \\ &\quad \times C_{1\lambda_d 2\mu}^{3\lambda_3} \mathcal{Y}_{2\mu}(\mathbf{p}_{\pi_1}, \mathbf{p}_{d\pi_2}) + (\pi_1 \leftrightarrow \pi_2), \end{aligned} \quad (42)$$

where $\mathcal{Y}_{2\mu}(\mathbf{p}_1, \mathbf{p}_2)$ denote the solid spherical harmonics, expressed as functions of two momentum vectors, and $\mu = \lambda_3 - \lambda_d$. The derivation of Eqs. (41)–(43) can be done straightforwardly using the canonical or the non-relativistic spin tensor formalism [110]. The detailed derivation can be found in [111].

The vertex functions are related to the partial decay widths as follows:

$$F_{R \rightarrow ab}(p_{ab}) = M_{ab} \sqrt{\frac{8\pi \Gamma_{R \rightarrow ab}^{(l)}(p_{ab})}{(p_{ab})^{2l+1}}}. \quad (44)$$

Further, for the partial decay widths with meson emission, we chose the standard parametrization

$$\Gamma_{R \rightarrow ab}^{(l)}(p) = \Gamma_{R \rightarrow ab}^{(l)} \left(\frac{p}{p_0} \right)^{2l+1} \left(\frac{p_0^2 + \Lambda_{ab}^2}{p^2 + \Lambda_{ab}^2} \right)^{l+1}, \quad (45)$$

while for the $pn \rightarrow \mathcal{D}_{03}$ vertex, we used the Gaussian form factor, according to the dibaryon model for NN interaction [67, 68]. In this case, the \mathcal{D}_{03} decay width into np channel has the form similar to Eq. (30). Parameters Λ_{ab} were fixed by a condition of a constant width near the resonance point, so we found $\Lambda_{\sigma d} = 0.18$, $\Lambda_{\pi\pi} = 0.09$, $\Lambda_{\pi D_{12}} = 0.12$ and $\Lambda_{\pi d} = 0.15$ GeV. For the latter parameter, we used also a higher value $\Lambda_{\pi d} = 0.3$ GeV which describes better the one-pion production process $pp \rightarrow d\pi^+$ (see Sec. 3).

The differential distribution on the invariant mass of two particles b and c can be found from the formula

$$\frac{d\sigma}{dM_{bc}} = \frac{1}{(4\pi)^5 p_s} \int \int p_a p_{bc} d\Omega_a d\Omega_{bc} \overline{|\mathcal{M}(\mathbf{p}_a, \mathbf{p}_{bc})|^2}, \quad (46)$$

where \mathbf{p}_a is a c.m. 3-momentum of the particle a , \mathbf{p}_{bc} the particle b momentum in c.m.s. of two particles b and c , and the line over the matrix element squared stands for averaging over the initial and summing over the final spin states. Then one gets for the total cross section:

$$\sigma = \int_{m_b+m_c}^{\sqrt{s}-m_a} dM_{bc} \frac{d\sigma}{dM_{bc}}. \quad (47)$$

The significance of the σ -production mechanism for description of the $M_{\pi\pi}$ spectrum and the ABC effect was shown in Ref. [51]. Here we concentrate on the second mechanism, i.e., $\mathcal{D}_{03} \rightarrow \mathcal{D}_{12} + \pi \rightarrow d + \pi\pi$, which contains the transition between isoscalar and isovector dibaryons. The most sensitive quantity to the parameters of the \mathcal{D}_{12} dibaryon is the distribution on the invariant mass $M_{d\pi}$, while the total cross section as well as the $M_{\pi\pi}$ distribution are only slightly renormalized when changing the \mathcal{D}_{12} parameters. Fig. 10 shows the $M_{d\pi}$ distribution in the reaction $pn \rightarrow d\pi^0\pi^0$ at the peak energy $\sqrt{s} = 2.38$ GeV. Contrary to the supposition made at the beginning of this section, we found this distribution to be quite weakly dependent on the parameter $\Lambda_{\pi d}$. An increase of $\Lambda_{\pi d}$ from 0.15 to 0.3 GeV leads to only a small narrowing and increasing the peak by about 10%, thus worsening somewhat the agreement with experiment. However, when using a slightly modified set of parameters for the dibaryon \mathcal{D}_{12} , i.e., $M'_{\mathcal{D}_{12}} = 2155$ MeV, $\Gamma'_{\mathcal{D}_{12}} = 103$ MeV and $\Lambda'_{\pi d} = 0.25$ GeV (see set B in Table I), which gives an accurate description of the partial 1D_2P cross section in the one-pion production process, we got an almost accurate description of the $M_{d\pi}$ distribution in 2π production as well (cf. thin solid lines in Figs. 6 and 10), the main improvement being given again by a small increase in the \mathcal{D}_{12} mass. This indicates the possibility of a very good *simultaneous description of the independent empirical data* for one- and two-pion production processes with the same realistic parameters of the \mathcal{D}_{12} dibaryon.

On the other hand, we found that changing the \mathcal{D}_{12} mass by 10–20 MeV does not lead to any shift of the resonance peak position in the $M_{d\pi}$ spectrum in the 2π production process, in contrast to the cross section of the one-pion production reaction $NN \rightarrow d\pi$. This reflects the fact that all final distributions in the reaction $pn \rightarrow d(\pi\pi)_0$ must be symmetrized over two outgoing pions. As a consequence of this symmetry, simultaneous changes in two individual distributions for each pion largely cancel each other and

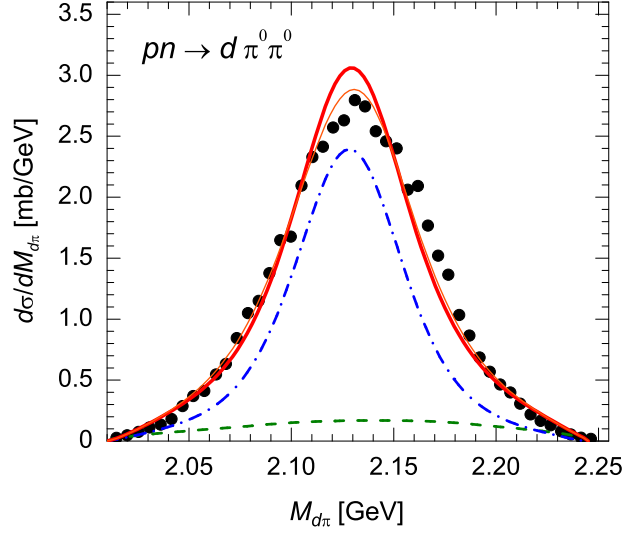


Figure 10: (Color online) Distribution on the invariant mass of the $d\pi$ system in the reaction $pn \rightarrow d\pi^0\pi^0$ at $\sqrt{s} = 2.38$ GeV. Thick solid line corresponds to the parameters of the isovector dibaryon \mathcal{D}_{12} fixed in Sec. 3 (see Table 1, set A) and thin solid line was obtained using slightly modified parameters (set B). The individual contributions of the two decay modes of the \mathcal{D}_{03} dibaryon, i.e., via an intermediate state $\mathcal{D}_{12} + \pi$ (dot-dashed line) and through a light scalar σ -meson emission (dashed line), calculated with the first set of parameters, are also shown. The filled circles correspond to the WASA@COSY experimental data [40] renormalized according to [41].

are therefore weakly reflected in a final (observed) distribution. Given this fact, it is not surprising that the $M_{d\pi}$ distribution is well reproduced also by a mechanism $\mathcal{D}_{03} \rightarrow \Delta\Delta$ [39, 40], without the formal account of the \mathcal{D}_{12} dibaryon. In this case, each individual-pion distribution on the $d\pi$ invariant mass peaks near the $N\Delta$ threshold located 20 MeV above the \mathcal{D}_{12} mass. However, the final symmetrized $M_{d\pi}$ distribution turns out to be almost the same as in case of intermediate \mathcal{D}_{12} excitation. This makes difficult to disentangle the two \mathcal{D}_{03} decay routes, i.e., $\mathcal{D}_{03} \rightarrow \mathcal{D}_{12} + \pi$ and $\mathcal{D}_{03} \rightarrow \Delta\Delta$. From a general viewpoint, of course, one has to take both these routes into account. However, it is known from numerous six-quark microscopic calculations [23, 112, 113] that the wave function of the Δ - Δ system in the $I(J^P) = 0(3^+)$ channel (corresponding to the \mathcal{D}_{03} resonance) has a very small mean square radius $r_{\Delta\Delta} \simeq 0.7$ – 0.9 fm, that is, two Δ isobars in this state are almost completely overlapped with each other. Therefore it seems

natural to assume that the main hadronic component of the \mathcal{D}_{03} dibaryon, i.e., $\Delta\Delta$, is not a physical system of two isolated Δ isobars, which is highly unstable ($\Gamma_{\Delta\Delta} \simeq 2\Gamma_{\Delta} \simeq 235$ MeV), but only a specific $6q$ -configuration with quantum numbers of the $\Delta\Delta$ system. It is also confirmed by an experimental observation that the \mathcal{D}_{03} resonance width is much smaller than the total width of two isolated Δ isobars: $\Gamma_{\mathcal{D}_{03}} \simeq 70$ MeV $\ll \Gamma_{\Delta\Delta}$. In this context, the independent pion decay of two strongly overlapped Δ isobars assumed in [39, 40] seems not fully justified from physical point of view. Therefore, it seems more reasonable to suggest that at least one of the final pions should be emitted from a dibaryon state, i.e., from the compact $6q$ object surrounded by meson fields, but not from an isolated Δ isobar. One also needs to take into account that the width of the intermediate $\mathcal{D}_{12} + \pi$ state is about half the width of the $\Delta + \Delta$ state, and thus the lifetime of the first is two times longer. So, the decay of the \mathcal{D}_{03} resonance via the intermediate state $\mathcal{D}_{12} + \pi$ rather than $\Delta + \Delta$ is likely to be regarded as the dominant one, although both above dibaryons can formally be described in terms of intermediate $\Delta\Delta$ and $N\Delta$ states [52].

The total cross section of the reaction $pn \rightarrow d\pi^0\pi^0$, going through the formation of the intermediate dibaryon $\mathcal{D}_{03}(2380)$ with a total width $\Gamma_{\mathcal{D}_{03}} = 70$ MeV, is shown in Fig. 11. We obtained a very good agreement with experimental data at energies close to the resonance peak using the Gaussian form factor in the $pn \rightarrow \mathcal{D}_{03}$ vertex with a scale parameter $\alpha(\mathcal{D}_{03}) = 0.35$ GeV which turned out to be larger than that for the $pp \rightarrow \mathcal{D}_{12}$ vertex $\alpha(\mathcal{D}_{12}) = 0.25$ GeV. This result seems quite natural because the isoscalar resonance \mathcal{D}_{03} , according to quark-model estimates (see, e.g., [23]), is characterized by a smaller radius than the isovector resonance \mathcal{D}_{12} .

On the other hand, Fig. 11 shows rather large discrepancies between our theoretical calculation and experimental data beyond the resonance peak. Particularly strong deviations are observed at energies $\sqrt{s} \gtrsim 2.43$ GeV. It is well known however [40] that a significant contribution at these energies can be given by the conventional mechanism based on t -channel excitation of the intermediate Δ - Δ system [108, 114], being produced near its threshold $(\sqrt{s})_{\Delta\Delta} = 2.46$ GeV. An additional enhancement of the cross section near the $\Delta\Delta$ threshold can come from interference between the background t -channel process and the resonance \mathcal{D}_{03} contribution which is though relatively small but still non-zero in this energy region (see Fig. 11).

The next important and nontrivial step towards establishing a connection between different hadronic processes and intermediate dibaryon resonances,

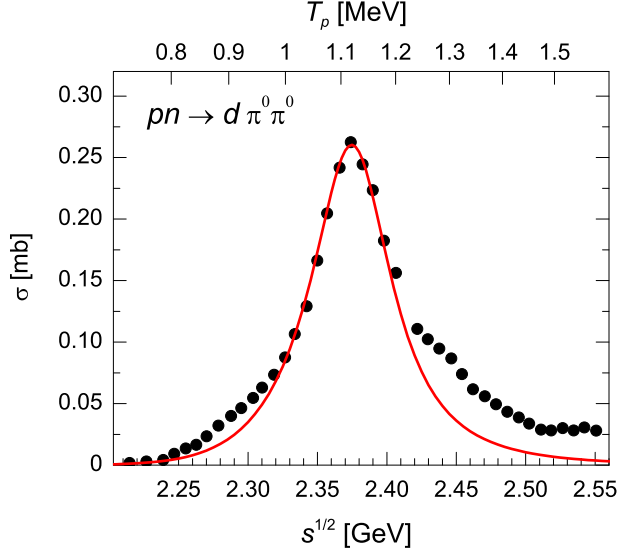


Figure 11: (Color online) Total cross section of the reaction $pn \rightarrow d\pi^0\pi^0$. The solid line shows the calculation in the dibaryon model which includes excitation of the isoscalar resonance $\mathcal{D}_{03}(2380)$ with the total width $\Gamma_{\mathcal{D}_{03}} = 70$ MeV. Filled circles correspond to the WASA@COSY experimental data [40] renormalized according to [41].

is searching for isovector dibaryon signals in the processes of two-pion production in pp collisions.

4.2. Isovector dibaryon signals in 2π production in pp collisions

To the present authors' knowledge, excitation of intermediate dibaryon resonances in two-pion production processes in *isovector* NN channels, like $pp \rightarrow d\pi^+\pi^0$, $pp \rightarrow pp\pi^0\pi^0$, etc., has not yet been considered in the literature. In fact, the mass of the basic isovector dibaryon \mathcal{D}_{12} lies just at the 2π -production threshold $(\sqrt{s})_{NN\pi\pi} = (2m_p + 2m_{\pi^0}) \approx 2.15$ GeV, so its decay with two-pion emission is very unlikely. However the higher-lying isovector dibaryons found in pp elastic scattering in partial waves 3F_3 , 1G_4 , etc. [5, 94], if they really exist, should decay into $d\pi\pi$ and $NN\pi\pi$ channels with a higher probability. Thus, the dibaryon $\mathcal{D}_{13}^-(2220)$ (3F_3) should be excited in pp collisions at energies $T_p = (M_D^2/2m_p - 2m_p) \approx 750$ MeV, the dibaryon $\mathcal{D}_{14}(2430)$ (1G_4) — at $T_p \approx 1.3$ GeV, etc. The possibility of finding the signals of these dibaryons in the 2π -production cross sections is determined mainly by the relative contributions of the resonance and background processes. However, as

was already outlined above, one might expect the contributions of the background meson-exchange mechanisms (with relatively soft vertex cut-offs) to the two-pion production to be significantly less than to elastic scattering or one-pion production, since 2π production is generally accompanied by larger momentum transfers.

The conventional mechanisms of 2π production in pp collisions at energies $T_p \sim 1$ GeV are based on t -channel excitation of the intermediate “pseudoresonance” systems NR ($T_p \simeq 0.9$ – 1.1 GeV), where R is the Roper resonance $N^*(1440)$, and $\Delta\Delta$ ($T_p \simeq 1.3$ – 1.4 GeV). So, one may assume that the above meson-exchange mechanisms can interfere with the true resonance ones based on formation of intermediate isovector dibaryons. It should be borne in mind that the mass of the $\mathcal{D}_{14}(2430)$ dibaryon lies very close to the $\Delta\Delta$ -excitation threshold $(\sqrt{s})_{\Delta\Delta} = 2.46$ GeV, so that the contribution of this dibaryon resonance may be difficult to separate from the contribution of the conventional t -channel $\Delta\Delta$ process. One faces here in principle the same problems as in determining the relative contributions of the true resonance $\mathcal{D}_{12}(2150)$ and the “pseudoresonance” $N\Delta$ when studying the one-pion production processes. However, it should be emphasized once again that, due to shorter-range nature of the 2π -production processes, formation of a compact six-quark object (dibaryon) in this case can have a higher probability than the much more peripheral t -channel meson exchange, if the latter is calculated with the use of realistic (soft) vertex form factors. On the other hand, the mass of the resonance $\mathcal{D}_{13}^-(2220)$ lies 100–200 MeV below the excitation energies of the NR system, so that the signal of this dibaryon at energies $T_p \simeq 700$ – 800 MeV can in principle be seen above the background, although the total cross sections of 2π production are very small in this energy region (2–3 μb only).

Let’s consider the reaction $pp \rightarrow pp\pi^0\pi^0$, for which high-statistics experimental data in a broad energy range exist [115]. The most intriguing feature of the total cross section of just this reaction (contrary to the other $NN \rightarrow NN\pi\pi$ channels) is a “shoulder” at energies $T_p = 1$ – 1.2 GeV (see Fig. 12), which is followed by a rapid increase as the energy approaches the $\Delta\Delta$ excitation threshold. The conventional model of the Valencia group [116], based on t -channel excitation of the intermediate states NR and $\Delta\Delta$, even with high cut-off parameters in meson-baryon vertices

taken from the Bonn NN -potential model [85],⁸ does not reproduce the observed behavior of experimental data because the theoretical cross section in this model increases uniformly with rising energy. Aside from the Valencia model, the most recent attempt to describe two-pion production solely by t -channel meson-exchange mechanisms was made by Cao et al. [117]. Their model includes all nucleon resonances with masses up to 1.72 GeV and gives a good reproduction of the total and also some measured differential cross sections for six $NN \rightarrow NN\pi\pi$ channels up to beam energies of 2.2 GeV, however, also fails in reproduction of the data for the $pp \rightarrow pp\pi^0\pi^0$ at energies $T_p \simeq 1.1$ – 1.2 GeV. In fact, the reaction $pp \rightarrow pp\pi^0\pi^0$ is the only two-pion production process in pp collisions where an almost purely isoscalar $\pi\pi$ pair (with a small isotensor admixture) is produced. In this channel, the isovector dibaryon contributions should be enhanced due to intermediate σ -meson production (though this enhancement would be less significant than for the isoscalar dibaryon \mathcal{D}_{03} — see Sec. 5.2). Other $\pi\pi$ -production channels in pp collisions contain large contributions from isovector $\pi\pi$ pairs which can be described basically by the background processes (t -channel $\Delta\Delta$ excitation, etc.) [117]. On the other hand, the experimental data for $pp \rightarrow pp\pi^0\pi^0$ reaction can be qualitatively explained by assuming the dominant contribution of the two known dibaryon candidates: $\mathcal{D}_{13}^-(2220)$ at $T_p \simeq 750$ MeV and $\mathcal{D}_{14}(2430)$ at $T_p \simeq 1.3$ GeV. In this case, the total cross section of the reaction $pp \rightarrow pp(\pi\pi)_0$ can be described by the formula

$$\sigma = \sum_{J=3,4} \frac{\pi(2J+1)}{p^2} \frac{2s\Gamma_{D_J}^{(i)}(s)\Gamma_{D_J}^{(f)}(s)}{(s - M_{D_J}^2)^2 + s\Gamma_{D_J}^2(s)}, \quad (48)$$

where $\Gamma_{D_J}^{(i)}(s)$ and $\Gamma_{D_J}^{(f)}(s)$ denote the partial widths of the resonance with a total angular momentum J for the incoming (pp) and outgoing ($pp\pi^0\pi^0$) channels. As a first approximation, the total widths of the two resonances can be assumed constant and equal to $\Gamma_{D_J} = 150$ MeV. The incoming partial widths $\Gamma_{D_J \rightarrow pp}$ can also be considered constant in this energy range, but for comparison of the theoretical calculations with experimental data near the 2π -production threshold one needs to take into account somehow the energy dependence of the outgoing widths $\Gamma_{D_J \rightarrow pp\pi^0\pi^0}$. In fact, they are proportional

⁸Note that t -channel $\Delta\Delta$ process is even more sensitive to the cut-off parameter in the $\pi N\Delta$ vertex than the $N\Delta$ mechanism in one-pion production since the first process contains *two* such vertices.

to the factor $(s - 4(m + m_\pi)^2)^n$, where the exponent n , in general, depends on the reaction dynamics. We found that the energy dependence of the total cross section for the reaction $pp \rightarrow pp\pi^0\pi^0$ in the near-threshold region can be reproduced well with $n = 4$. The above factor also significantly distorts the Breit–Wigner form of the energy distributions corresponding to the suggested resonances.

The results of calculations using Eq. (48), as well as the predictions of the Valencia [116] and Beijing [117] models are shown in Fig. 12. In order to reproduce the experimental cross section in the vicinity of the incoming proton energies $T_p = 750$ MeV and 1.3 GeV, corresponding to the maximal excitation of the above two isovector resonances, their widths should satisfy the relations: $\Gamma^{(i)}\Gamma^{(f)}/\Gamma^2 \simeq 2.2 \times 10^{-5}$ and 2.7×10^{-3} for the \mathcal{D}_{13}^- and \mathcal{D}_{14} dibaryons, respectively. If to suggest the incoming (elastic) partial widths of these dibaryons to be $\simeq 10\%$ of their total widths (as for the \mathcal{D}_{12} resonance) then we obtain the following estimates for the branching ratios of the $pp\pi^0\pi^0$ channel: $\Gamma_{D_{13}^- \rightarrow pp\pi^0\pi^0}/\Gamma_{D_{13}^-} \simeq 0.02\%$ and $\Gamma_{D_{14} \rightarrow pp\pi^0\pi^0}/\Gamma_{D_{14}} \simeq 3\%$. These estimates, as follows from Eq. (48), do not depend on neither the absolute values of the partial and total widths, nor the parametrization of their energy dependence. So, one can see that a very small fraction of the $pp\pi^0\pi^0$ channel in the isovector dibaryon decay widths is sufficient to describe the total cross section of the reaction $pp \rightarrow pp\pi^0\pi^0$ in terms of intermediate dibaryons only.

In a more realistic calculation, of course, one has to take into account the interference of the dibaryon excitation mechanisms with the background processes, mainly the t -channel $\Delta\Delta$ and NR excitation processes. However, one can see already now that the dibaryon model, even in its simplest form presented here, describes the data on $pp \rightarrow pp\pi^0\pi^0$ reaction in a rather broad energy range not worse and even better than the conventional model based on t -channel excitation of hadronic resonances.

In the recent work of the WASA@COSY Collaboration [118], the total cross section of a similar reaction $pn \rightarrow pn\pi^0\pi^0$ in the GeV region has been measured. Experiment clearly shows an enhancement due to the isoscalar resonance $\mathcal{D}_{03}(2380)$ production at energies $T_p \simeq 1.1$ GeV. Therefore, it seems quite natural that the isovector dibaryons $\mathcal{D}_{13}^-(2220)$ and $\mathcal{D}_{14}(2430)$ can be manifested in the reaction $pp \rightarrow pp\pi^0\pi^0$ at relevant energies (though the isovector resonance peaks will be smeared in comparison to a more pronounced isoscalar peak due to the larger widths of isovector resonances).

We also calculated the contribution of the same dibaryon resonances

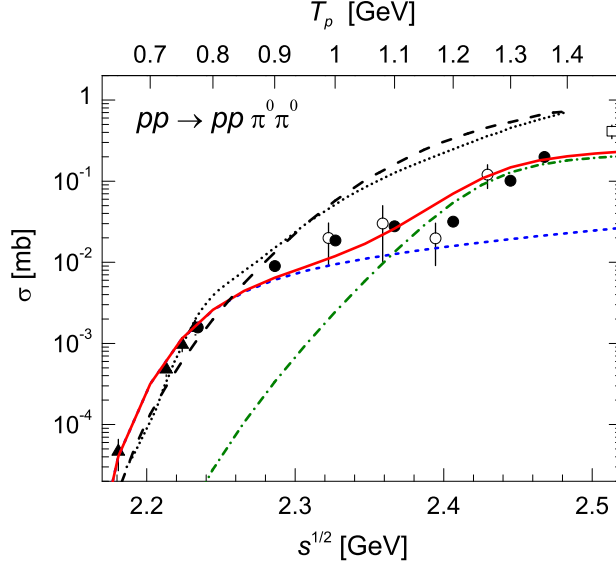


Figure 12: (Color online) Total cross section of the reaction $pp \rightarrow pp\pi^0\pi^0$. The solid line shows the calculation in a model including the excitation of two intermediate dibaryon resonances $\mathcal{D}_{13}^-(2220)$ and $\mathcal{D}_{14}(2430)$. The individual contributions of the two resonance mechanisms are shown by short-dashed and dash-dotted lines, respectively. The dotted line corresponds to the Valencia model calculations [116] with account of t -channel excitation of intermediate NR and $\Delta\Delta$ states. The long-dashed line shows the calculations of Cao et al. [117] which include all nucleon resonances with masses up to 1.72 GeV. The CELSIUS/WASA experimental data are shown by filled symbols and the older bubble-chamber data — by open symbols (see [115] and references therein).

$\mathcal{D}_{13}^-(2220)$ and $\mathcal{D}_{14}(2430)$ (decaying with emission of an isoscalar $\pi\pi$ pair) to the total cross section of the reaction $pp \rightarrow pp\pi^+\pi^-$. This contribution, apart from isospin violation due to the mass difference between the neutral and charged pions, would be just twice the contribution to the reaction $pp \rightarrow pp\pi^0\pi^0$. The results of our calculation together with experimental data and the Beijing model predictions are shown in Fig. 13. Here, contrary to the reaction $pp \rightarrow pp\pi^0\pi^0$, the dibaryon contributions are rather small everywhere except for the near-threshold region. This result is not surprising given the fact that the isovector $\pi\pi$ pairs should be produced with a high probability in this reaction, however, their production is suppressed near the threshold due to Bose symmetry (isovector $\pi\pi$ pairs can be in odd partial waves only). The isovector dipion production is described well by the conven-

tional meson-exchange models, as is also seen from Fig. 13. Thus, one could expect manifestation of the intermediate dibaryons in processes where the isoscalar pion-pair production dominates, since the dibaryon in such cases can emit an intermediate σ -meson which enhances the probability of such a resonance mechanism. The signal of the near-threshold σ -meson production can also be seen in the $\pi\pi$ invariant-mass distribution for the reaction $pp \rightarrow pp\pi^0\pi^0$ which is concentrated near threshold and cannot be described by the conventional meson-exchange models (see [117]). This feature can be regarded as some kind of the ABC effect in pp collisions: though there is no significant enhancement over the phase-space distribution (as in the $pn \rightarrow d(\pi\pi)_0$ reaction), there is a noticeable near-threshold enhancement over the conventional model calculations (see also Sec. 5.2). We should also add here that the essential flatness of the angular distributions in the reaction $pp \rightarrow pp\pi^0\pi^0$ does not contradict the interpretation of this reaction in terms of intermediate dibaryons. Although the dibaryon resonances considered here have high angular momenta, the integration over the four-particle phase space and also interference with background processes can flatten the observed angular distributions. Indeed, as was shown in Ref. [115], the angular distributions in the $pp \rightarrow pp\pi^0\pi^0$ reaction in case of the limited phase space (^2He scenario) are much more anisotropic than for the full four-particle phase space.

At the end of this section, it is interesting to note that some attempts were made recently to modify the conventional Valencia model [116] in order to describe the numerous new data [115] on 2π production in pp collisions. It was found [115] that for reproducing the basic features of the total and differential cross sections in the reaction $pp \rightarrow pp\pi^0\pi^0$, it is necessary to reduce the ρ -meson exchange in the original model [116] by an order of magnitude (i.e., almost remove it). Furthermore, the meson-baryon vertex form factors were dropped in this modified version of the model. In fact, such a modification corresponds to the account of the pion-exchange only, with the cut-off parameter $\Lambda = \infty$. Although this model is hardly consistent with the actual physical picture, it describes the data very well [115]. One could see here an interesting parallel with the above-cited work [87], where the deuteron properties were accurately described in a model including only pion exchange with $\Lambda = \infty$, as well as with Ref. [70], where the total $\pi^+d \rightarrow pp$ cross section in a broad energy range was shown to be described reasonably (though with incorrect normalization) within the same model. All these observations might probably be related to the general principle of continuity between hadron

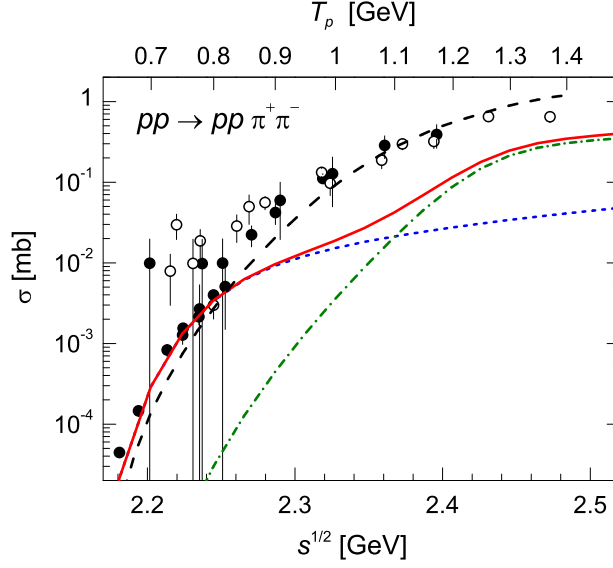


Figure 13: (Color online) Total cross section of the reaction $pp \rightarrow pp\pi^+\pi^-$. The meaning of theoretical curves is the same as in Fig. 12. The dibaryon model calculation (solid line) includes the isoscalar $\pi^+\pi^-$ channel only. The experimental data are shown by filled and open circles (see references in [117]).

and quark d.o.f.

Thus, we have demonstrated that the one- and two-pion production processes in NN collisions can be consistently described in the model involving excitation of intermediate dibaryon resonances with realistic parameters. It has also been shown that the dibaryon parameters used do not contradict the empirical data on elastic NN and πd scattering.

To further clarify the relative role of the resonance and background contributions to the one- and two-pion production reactions in the GeV region, the more detailed knowledge of the basic dibaryon parameters, along with independent confirmation of the soft cut-off parameters in traditional meson-exchange mechanisms is required. However, as will be shown below, even at the present stage of our knowledge, an analysis of the inner structure and possible decay modes of intermediate dibaryons allow to give a qualitative explanation for some important experimental observations which find no obvious explanation within the conventional models.

5. Two-pion production and dibaryon spectroscopy

In this section, we analyze the large differences between two-pion production cross sections in pn and pp collisions in the energy region $T_p \sim 1$ GeV in terms of intermediate dibaryon resonances and their spectra. In fact, the total cross section for production of the scalar-isoscalar pion pairs, i.e., $\pi^0\pi^0$ or $(\pi^+\pi^-)_0$, in pn collisions at energies $T_p = 1.1$ – 1.2 GeV was found [118, 115] to be an order of magnitude higher than that in pp collisions. This difference was interpreted [118] as a consequence of the isoscalar dibaryon $\mathcal{D}_{03}(2380)$ excitation which occurs in pn collisions only. It is important to emphasize that *elastic cross sections* for np and pp scattering are, on the contrary, very close to each other in the same energy region. Furthermore, the $\pi\pi$ invariant mass distribution in the reaction $pn \rightarrow d(\pi\pi)_0$ exhibits a pronounced near-threshold enhancement (the ABC effect) [40, 41], whereas such an enhancement in the reaction with similar kinematics $pp \rightarrow pp(^1S_0)\pi^0\pi^0$ turns out to be very modest, if present at all [115].

In our previous work [51], an abnormally high yield of the near-threshold scalar-isoscalar pion pairs observed in pn collisions was quantitatively interpreted as a result of constructive interference between two mechanisms of the $\mathcal{D}_{03}(2380)$ resonance decay: a direct decay to the final deuteron with emission of a light scalar σ meson (accompanied by a partial chiral symmetry restoration in a highly excited dibaryon state [51]) and two consecutive one-pion decays via an intermediate isovector dibaryon $\mathcal{D}_{12}(2150)$ production. While the latter mechanism of sequential decay gives the rather uniform $M_{\pi\pi}$ distribution, the mechanism of the σ -meson emission, though having a very small branching ratio, is highly concentrated near the two-pion threshold.

If we now suppose (see the previous section) that two-pion production in pp collisions in the GeV region occurs also to a large extent via intermediate (isovector) dibaryons formation, then it would be interesting to investigate the reasons for presence of the large ABC effect in pn and its almost absence in pp collisions from this point of view. For this purpose, it is important first to establish the relationship between isoscalar and isovector dibaryons, as well as the impact of their possible quark structure on the probability of two-pion production.

5.1. Quark-cluster model for dibaryons

The parameters (masses and total widths) for the main dibaryon candidates determined from experiments and predicted theoretically [17] on the

basis of SU(6) symmetry are summarized in Table II. Dibaryon candidates are presented in the Table in order of decreasing experimental evidence. Thus, there is solid experimental evidence for $\mathcal{D}_{01}(1.88)$ (the deuteron), $\mathcal{D}_{10}(1.88)$ (the singlet deuteron) and $\mathcal{D}_{03}(2.38)$, disputable evidence for $\mathcal{D}_{12}(2.15)$, $\mathcal{D}_{13}^-(2.22)$ and $\mathcal{D}_{12}^-(2.18)$ ⁹, and only experimental hints for $\mathcal{D}_{14}(2.43)$, $\mathcal{D}_{15}^-(2.70)$ and $\mathcal{D}_{16}(2.90)$. In quoting the parameters of isovector dibaryons in Table II we follow mainly the summary paper of Yokosawa [94] and also give references to some original papers concerning these resonances. Two theoretically predicted dibaryons with high isospins [17] which have not yet been seen experimentally (see, however, [48]) are also presented in Table II.

Table 2: Parameters of dibaryon resonances (in GeV) found from experiments in comparison with theoretical predictions [17] (the last column).

\mathcal{D}_{IJ}	$I(J^P)$	$^{2S+1}L_J^{(NN)}$	M_D^{exp}	Γ_D^{exp}	Refs.	$M_D^{\text{SU}(6)}$
$\mathcal{D}_{01}(1.88)$	$0(1^+)$	3S_1	1.88	0		1.88
$\mathcal{D}_{10}(1.88)$	$1(0^+)$	1S_0	1.88	$\simeq 0$		1.88
$\mathcal{D}_{03}(2.38)$	$0(3^+)$	3D_3	2.38 ± 0.01	0.08 ± 0.01	[40, 46]	2.35
$\mathcal{D}_{12}(2.15)$	$1(2^+)$	1D_2	2.14–2.17	0.08–0.14	[9, 55, 57]	2.16
$\mathcal{D}_{13}^-(2.22)$	$1(3^-)$	3F_3	2.20–2.25	0.1–0.2	[11, 53, 57]	—
$\mathcal{D}_{12}^-(2.18)$	$1(2^-)$	3P_2	2.17–2.20	0.1–0.2	[58, 94]	—
$\mathcal{D}_{14}(2.43)$	$1(4^+)$	1G_4	2.43–2.50	$\simeq 0.15$	[9, 11, 94]	—
$\mathcal{D}_{15}^-(2.70)$	$1(5^-)$	3H_5	2.70 ± 0.1	$\simeq 0.15$	[11, 13, 94]	—
$\mathcal{D}_{16}(2.90)$	$1(6^+)$	1I_6	2.90 ± 0.1	$\simeq 0.15$	[11, 13, 94]	—
\mathcal{D}_{21}	$2(1^+)$	—	?	?		2.16
\mathcal{D}_{30}	$3(0^+)$	—	?	?		2.35

Although the isovector dibaryons have not reached the clear-cut experimental evidence up to now, they were predicted by a number of theoretical QCD-inspired models. Regarding the possible quark structure of these dibaryons, one can follow theoretical arguments and the respective models developed by the Nijmegen [19] and ITEP [20] groups, based partly on estimates for the masses of multiquark clusters obtained in the MIT bag model. According to these models, the isovector dibaryons with $J^P = 2^+, 3^-, 4^+, 5^-, \dots$, observed in $\vec{p} + \vec{p}$ scattering as very inelastic resonances, have the two-cluster

⁹Note that this isovector dibaryon has been observed just recently by the ANKE Collaboration in the reaction $pp \rightarrow \{pp\}_s \pi^0$ [119].

quark structure $[q^4 - q^2]$, i.e., consist of a tetraquark q^4 and a diquark q^2 connected by a colored QCD string. The tetraquark with a mass $M(q^4) = 1.05\text{--}1.15$ GeV has the quantum numbers¹⁰ ($S = 1, T = 0$), while the diquark here is an axial one, i.e., with quantum numbers ($S = T = 1$) and a mass $M(q_A^2) = 450\text{--}550$ MeV. In general, because the whole dibaryon states are colorless, while the quark clusters q^4 and q^2 as well as the string between them are colored objects, one is dealing in this case with a “hidden color” (first predicted by Brodsky et al. [120, 121]; see also the recent paper [122]). So, the isovector and isoscalar dibaryons considered here can be classified as the typical hidden-color objects.

Next, according to [20], the observed series of isovector dibaryons lies on a relativistic Regge trajectory which describes rotational excitations of a relativistic string connecting two multiquark clusters. An important contribution to dibaryon masses is also given by the spin-orbit interaction between the quark clusters and the rotating string [20]. In this case, the trajectory of isovector dibaryon states on the graph $[J, M_D^2]$ (where J is a total dibaryon angular momentum) does not necessarily correspond to a straight line.

On the other hand, for relatively low energies of the rotational excitation $E^* = \Delta M \ll M_0$, where M_0 is a mass of the lowest rotational state, one can use the non-relativistic description of the rotational excitations in a clustered system $[q^4 - q^2]$ with an orbital angular momentum L between the quark clusters. For successively increasing values of $L = 0, 1, 2, 3, \dots$, one obtains the respective isovector dibaryons with alternating parities:¹¹ $\mathcal{D}_{12}(2.15)$, $\mathcal{D}_{13}^-(2.22)$, $\mathcal{D}_{14}(2.43)$, $\mathcal{D}_{15}^-(2.7)$, \dots . In this case, the rotational band of isovector dibaryons can be described by a simple non-relativistic formula (corresponding to the model of a rigid rotor) for the rotational states in the $[q^4 - q^2]$ system, with an additional term M_{LS} due to the spin-orbit interaction:

$$M_D(L) = M_0 + \beta \frac{\hbar^2}{2\mathcal{I}} L(L+1) + M_{LS}, \quad (49)$$

where \mathcal{I} is a moment of inertia for the rotating quark-cluster system and the constant β takes into account the kinetic energy of the rotating string itself.

Dependence of the isovector dibaryon masses M_D on the quantity $L(L+1)$ is shown in Fig. 14. It is clearly seen that the masses of the known isovector

¹⁰We use the letters S and T for the spin and isospin of the multiquark clusters, in accordance with notations adopted in [20].

¹¹We omit the “+” superscript for the positive-parity states.

dibaryons are well fitted into a straight line. This gives a strong argument in favor of the above quark-cluster structure of dibaryons, with multiquark clusters at the ends of the rotating colored string, which is well described, at least for a few lowest states, by the non-relativistic rigid rotor model. In this case, the correction due to the spin-orbit interaction apparently does not lead to any significant deviation from a straight line on a graph $[L(L+1), M_D]$.

It is interesting to note that in some previous works (see, e.g., [123]) the same isovector dibaryons were considered as lying on a rotational band in the NN system, in the spirit of rotational bands in nuclear physics. It was found [123] that the trajectory of isovector dibaryons on the graph $[L_{NN}(L_{NN}+1), M_D]$, where $L_{NN} = L+2 = J$, is also rather close to a straight line. However, since the dibaryons are known to be highly inelastic in the NN channel, the description in terms of quark clusters $[q^4 - q^2]$ rather than $[N - N]$ looks to be more appropriate.

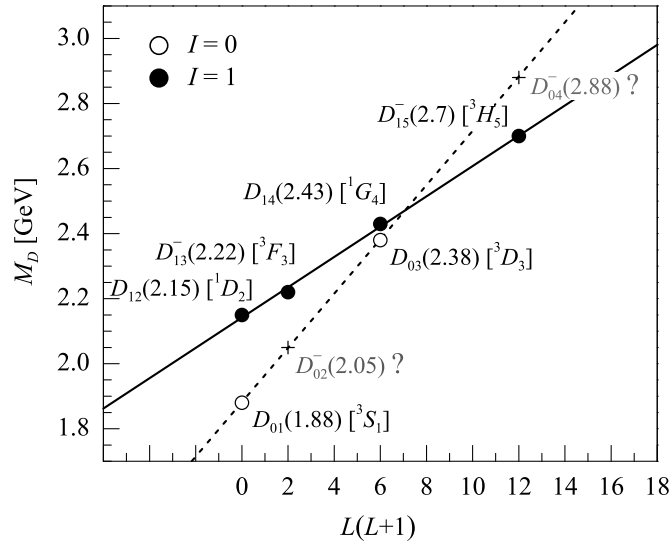


Figure 14: Dependence of the masses of known isovector and isoscalar dibaryon (six-quark) states on the square of the orbital angular momentum $L(L+1)$ between the tetraquark (q^4) and diquark (q^2) clusters. The dibaryon masses are given in parentheses, and the dominant partial waves of the NN system, in which the respective dibaryons can be excited, are shown in square brackets. The positions of hypothetical negative-parity isoscalar dibaryons uncoupled from the NN channel are marked by crosses.

In Fig. 14, the two known isoscalar dibaryons, i.e., the deuteron dibaryon

$\mathcal{D}_{01}(1.88)$ and the resonance $\mathcal{D}_{03}(2.38)$, are also shown. These dibaryons are actually different from their isovector analogues with the same orbital angular momentum L , i.e., $\mathcal{D}_{12}(2.15)$ and $\mathcal{D}_{14}(2.43)$, respectively, by replacing the axial diquark by a scalar one, having quantum numbers ($S = T = 0$). Accordingly, the spin-orbit interaction between the diquark and the colored string which shifts down the isovector dibaryon masses with $L > 0$ [20], should be turned off for their isoscalar partners. Then, assuming the isoscalar dibaryon series to be described by the above rigid rotor model, and drawing a straight line connecting the deuteron with the \mathcal{D}_{03} resonance, one can predict the existence of two isoscalar dibaryons of negative parity with masses lower than 3 GeV, namely, the $\mathcal{D}_{02}^-(2.05)$ and $\mathcal{D}_{04}^-(2.88)$. Since these dibaryons correspond to odd values of L and thus $L + S + I = L + 1$ is an even number, they should be uncoupled from the NN channel.

Actually, the dibaryon \mathcal{D}_{02}^- (or d') corresponding to $L = 1$ was predicted previously by both the Nijmegen [19] and ITEP [20] groups. Moreover, in the ITEP model [20], the d' dibaryon was predicted to have the same mass $M_{d'} \simeq 2.05$ GeV as we got here. Unfortunately, experimental searches for this dibaryon in previous years have not led to any unambiguous and convincing conclusions about its existence [124, 125]. The second negative-parity isoscalar dibaryon \mathcal{D}_{04}^- (which one might call d'^*) with a mass $M_{d'^*} \simeq 2.88$ GeV, as far as we know, is predicted *for the first time* in the present paper. So, the renewal of experimental search for these isoscalar dibaryons, as well as finding new confirmations and refining the parameters of the currently known isovector dibaryons seem to be the important further steps towards determining the true structure of the resonance $6q$ states.

According to the ITEP model [20], just the two-cluster structure with sufficiently separated multiquark clusters allows existence of the relatively long-lived $6q$ configurations with total widths $\Gamma_{6q} \simeq 100\text{--}150$ MeV, that is, of the same order as the Δ -isobar width. It is important to add here that the same effect of a $6q$ -system clustering into a tetraquark and a diquark was found also in S -wave NN interaction within the dibaryon model for nuclear force [67, 68]. Thus, clustering the dibaryons in the deuteron or singlet deuteron into a tetraquark $q^4(S = 1, T = 0)$ or $q^4(S = 0, T = 1)$, respectively, and a scalar diquark $q^2(S' = T' = 0)$ is achieved by a two-quantum ($2\hbar\omega$) excitation of a colored string with an orbital angular momentum $L = 0$. This $2\hbar\omega$ excitation (being a simple consequence of the dominating s^4p^2 [42] symmetry in the $6q$ system [67]) gives rise to a node in the radial wave function of the multiquark system, which corresponds exactly to the two-

cluster structure $[q^4 - q^2]$, although in this case the quark clusters are in a relative S wave. It is important to note that the same picture for S -wave NN interaction was found also in a fully microscopic calculation of the $6q$ system in the resonating group method [126, 127]. The authors [126, 127] (see also [128]) found that the two-cluster configuration $[q^4 - q^2]$ with a radial node in its relative-motion wave function dominates the six-quark wave function of the NN system in 3S_1 and 1S_0 channels. Thus, the clusterization of six-quark states seems to be a general phenomenon providing the relatively long-lived intermediate resonances in the NN interaction. So, it might play an essential role in the short-range nuclear force.

Given the above isovector and isoscalar rotational bands of dibaryons, one can consider the transitions between different dibaryon states via the meson emission. Thus, transitions between the eigenstates of two different bands can occur naturally via a pion emission changing a scalar diquark to an axial one and vice versa. Transitions within the same band can occur most likely via a string deexcitation through a light scalar (σ) meson emission. As was shown above, such transitions can generally be observed in one- or two-pion production processes in NN collisions however interfering with conventional processes involving intermediate baryonic resonances. The most “clear” case in this respect seems the pure isoscalar reaction $pn \rightarrow d(\pi\pi)_0$.

Now, using the above model for dibaryon resonances and also the results of Ref. [51], we consider the differences in the cross sections for two-pion production in pn and pp collisions at energies $T_p \sim 1$ GeV.

5.2. Comparison of 2π -production cross sections in pn and pp collisions

Here, we focus mainly on presence of the pronounced near-threshold enhancement (ABC effect) in the $M_{\pi\pi}$ spectrum in the isoscalar reaction $pn \rightarrow d(\pi\pi)_0$ and the near absence of it in the similar isovector reaction $pp \rightarrow pp(^1S_0)(\pi\pi)_0$. First of all, it is important to emphasize that, even in the isoscalar NN channel, a significant ABC effect is observed only in case of the *bound state* (the deuteron) formation in the final pn system. This fact was confirmed by the latest measurements [118] for the reaction $pn \rightarrow pn\pi^0\pi^0$, which revealed a strong \mathcal{D}_{03} resonance signal in the total cross section, but the very modest ABC enhancement in the $M_{\pi\pi}$ spectrum. From the first sight, as claimed in [118], it may pose a problem for the interpretation of the ABC effect [51] as a consequence of a light scalar σ meson production within the process $pn \rightarrow \mathcal{D}_{03} \rightarrow d + \sigma \rightarrow d + (\pi\pi)_0$. However, one should bear in mind that the $M_{\pi\pi}$ distribution in reaction $pn \rightarrow pn\pi^0\pi^0$ is obtained by an

integration over the available invariant masses M'_{pn} of the final pn pair. Since the σ -meson is emitted in the D wave from the \mathcal{D}_{03} decay, and this process is concentrated near the $M_{\pi\pi}$ threshold even in case of the final deuteron [51], the large centrifugal barrier will strongly suppress the σ -meson emission at higher M'_{pn} . Therefore, in the integrated $M_{\pi\pi}$ distribution, the $\mathcal{D}_{03} \rightarrow pn + \sigma$ branch and thus the ABC enhancement should be hardly visible, in accordance with experimental data [118]. Besides that, the process $\mathcal{D}_{03} \rightarrow d + \sigma$ is likely to be dynamically selected from other final pn configurations, since it represents a direct transition between two discrete eigenstates of the $6q$ system. On the contrary, the process $\mathcal{D}_{03} \rightarrow \mathcal{D}_{12} + \pi^0 \rightarrow pn\pi^0\pi^0$ will “survive” the M'_{pn} integration, since the decay of the resonance \mathcal{D}_{12} into $NN\pi$ channel is known to have a larger probability than that into $d\pi$ channel. This may reflect the fact that the isovector resonance \mathcal{D}_{12} have a large $N + \Delta$ component, with the rather weakly bound $N + \Delta$ system, unlike the deeply bound $\Delta + \Delta$ system in the isoscalar \mathcal{D}_{03} state. So, an intermediate $N + \Delta$ state can give a large contribution to the \mathcal{D}_{12} decay into $NN\pi$ channel. A detailed calculation is in order to test these qualitative considerations, however, our purpose in this section is to give just a qualitative insight into the differences between the observed cross sections for 2π production in different NN channels.

Let’s now turn to the 2π production reactions in the isovector NN channel. If one interprets the isoscalar dipion production in terms of intermediate dibaryons, then in case of pp collisions at energies $T_p \sim 1$ GeV, the two-pion emission should proceed most likely through the decay of intermediate isovector dibaryons¹² ${}^3F_3(2220)$ and ${}^1G_4(2430)$ (see Sec. 4). It is easy to see however that the direct transitions $\mathcal{D} \rightarrow pp({}^1S_0) + \sigma$, where \mathcal{D} is one of the above two dibaryons, with emission of a scalar σ meson, although possible in case of a low σ mass $m_\sigma \simeq 300$ MeV (which may follow from chiral symmetry restoration in an excited dibaryon [51]), will be suppressed by the centrifugal barrier, since the σ meson has to be emitted from the dibaryon 3F_3 or 1G_4 decay in F or G waves, respectively. For comparison, in case of the isoscalar dibaryon $\mathcal{D}_{03}(2380)$ decay into $d + \sigma$ channel, one has approximately the same available phase space as for the decay ${}^1G_4(2430) \rightarrow pp({}^1S_0) + \sigma$ (with the same mass of the σ meson), but the σ meson in first case is emitted in D

¹²For the reader’s convenience, we denote here the isovector dibaryons by the respective quantum numbers of the NN channel.

wave, thus leading to a pronounced ABC enhancement in the 2π invariant-mass spectrum in the $pn \rightarrow d(\pi\pi)_0$ reaction [51]. If we take into account the large width of the ${}^1G_4(2430)$ dibaryon, then it is also possible to consider the decay ${}^1G_4(2430) \rightarrow {}^1D_2(2150) + \sigma$ with the D -wave σ -meson emission, but this decay route will be suppressed due to the small available phase space.

Furthermore, the probability for the above isovector dibaryons to decay into the singlet deuteron ${}^1S_0(1880)$ with emission of a scalar σ meson should be additionally reduced because of the quark structure of these dibaryon states. In the quark-cluster model for dibaryons described above, the dibaryon component of the singlet deuteron has the structure $[q^4(S = 0, T = 1) - q^2(S' = T' = 0)]$, whereas the structure of dibaryons 3F_3 and 1G_4 is $[q^4(S = 1, T = 0) - q^2(S' = T' = 1)]$. Therefore, in two-pion emission from such isovector dibaryons, the one-pion transition of an axial diquark into a scalar one, i.e., $q^2(S' = T' = 1) \rightarrow q^2(S' = T' = 0)$, must be accompanied by a simultaneous one-pion Gamow–Teller transition in the tetraquark, i.e., $q^4(S = 1, T = 0) \rightarrow q^4(S = 0, T = 1)$. Hence the generation of a tightly correlated scalar-isoscalar pion pair under such conditions should be very unlikely. On the contrary, the isoscalar dibaryon $\mathcal{D}_{03}(2380)$ and the dibaryon component of the deuteron have the same quark-cluster structure $[q^4(S = 1, T = 0) - q^2(S' = T' = 0)]$, thus the σ meson is emitted here via a direct deexcitation of the colored string from a rotational level $L = 2$ to the ground level $L = 0$, i.e., without rearrangement of the quark clusters themselves.

Thus, in general, emission of a light scalar σ meson near the 2π threshold which can explain the significant ABC enhancement in the isoscalar NN channel, appears to be relatively suppressed in the isovector NN channel. As a result, one comes to a conclusion well confirmed by experiments [115], that the ABC effect in the reaction $pp \rightarrow pp(\pi\pi)_0$, including the limiting case $pp \rightarrow pp({}^1S_0)(\pi\pi)_0$, is very small, if visible at all (although it can still be manifested under certain kinematic conditions [129]).

Given the above arguments, it is possible to understand qualitatively the observed differences between two-pion production cross sections in pn and pp collisions. In this respect, the interpretation of 2π production in NN collisions in terms of generation of intermediate dibaryon resonances and their possible decay modes with two-pion emission seems to be rather appropriate and natural.

6. Conclusions

In this work, we analyzed the contributions of intermediate dibaryon resonances to the one- and two-pion production processes in NN collisions. Since these processes, in contrast to elastic scattering, are always accompanied by a large momentum transfer, i.e., involve the region of small internucleon distances, a very important role in description of such processes is played by the short-range mechanisms of NN interaction, based on quark structure of interacting nucleons. In particular, in the overlap region of two nucleons, the probability of generation of the compact six-quark objects, i.e., dibaryon resonances, can increase considerably. This conclusion is confirmed in the present study by a comparative analysis of contributions of s -channel dibaryon-formation and t -channel meson-exchange mechanisms to the elastic pp and π^+d scattering and the one-pion production reaction $pp \rightarrow d\pi^+$. An even more pronounced manifestation of intermediate dibaryon resonances is expected in two-pion production reactions. In addition to the continuing study of the isoscalar $0(3^+)$ resonance observed recently in two-pion production in pn collisions [40], we proposed searching the signals of isovector dibaryons in pp collisions.

However, as shown by numerous studies including the present work, the contributions of short-range QCD mechanisms can often be simulated rather accurately by the conventional meson-exchange mechanisms (with appropriate parameter fitting). This fact can explain the success of meson-exchange models in the description of many hadronic and electromagnetic processes including those with high momentum transfers. However, while the long-range part of NN interaction is described universally by t -channel meson-exchange mechanisms (mainly by one- and two-pion exchange) and poses no doubts, an effective description of its short-range part requires introducing the specific mechanisms and careful adjusting their parameters (mainly the vertex cut-offs) *ad hoc* to a particular process. These parameters entering the same mechanisms should be changed to describe the different processes and are often not consistent with microscopic predictions. As an example, one can consider the large differences between the short-range cut-off parameter in the $\pi N\Delta$ vertex, needed to describe elastic πN scattering, from parameters in the same vertex used in realistic potential models for NN interaction, in conventional models for one-pion production and others. In other words, the description of short-range processes in traditional meson-exchange models is not entirely consistent and contains a number of inner contradictions (see

discussion on this issue in [88]).

On the other hand, in effective description of the short-range QCD mechanisms of NN interaction by using dibaryon degrees of freedom, the dibaryon parameters used in calculations of various hadronic and nuclear processes are in a good agreement with each other. It is important to realize that QCD-motivated dibaryon mechanisms at small inter-nucleon distances do not contradict the traditional meson-exchange picture at the large and intermediate distances, but rather complement it. The dibaryon generation does not actually contradict also the heavy-meson exchange, provided the realistic (soft) cut-off parameters in the respective vertices are used. However, concerning generation of the heavy vector mesons ρ and ω at short NN distances, it seems more natural to assume these mesons emerging from a unified meson cloud of a six-quark object (dibaryon) than in t -channel exchange between two isolated nucleons at distances $r_{NN} \sim 0.2$ fm, where the quark cores of two nucleons are strongly overlapped (see the detailed discussion in [130]).

Thus, we believe that dibaryons are much more intriguing objects than just multiquark exotics, which might be manifested under specific experimental conditions. They seem to be a manifestation of the fundamental properties of nonperturbative QCD, which drive the NN interaction at short distances and, in general, the short-range correlations in nuclei. The quantitative verification of this hypothesis requires further theoretical and experimental research.

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